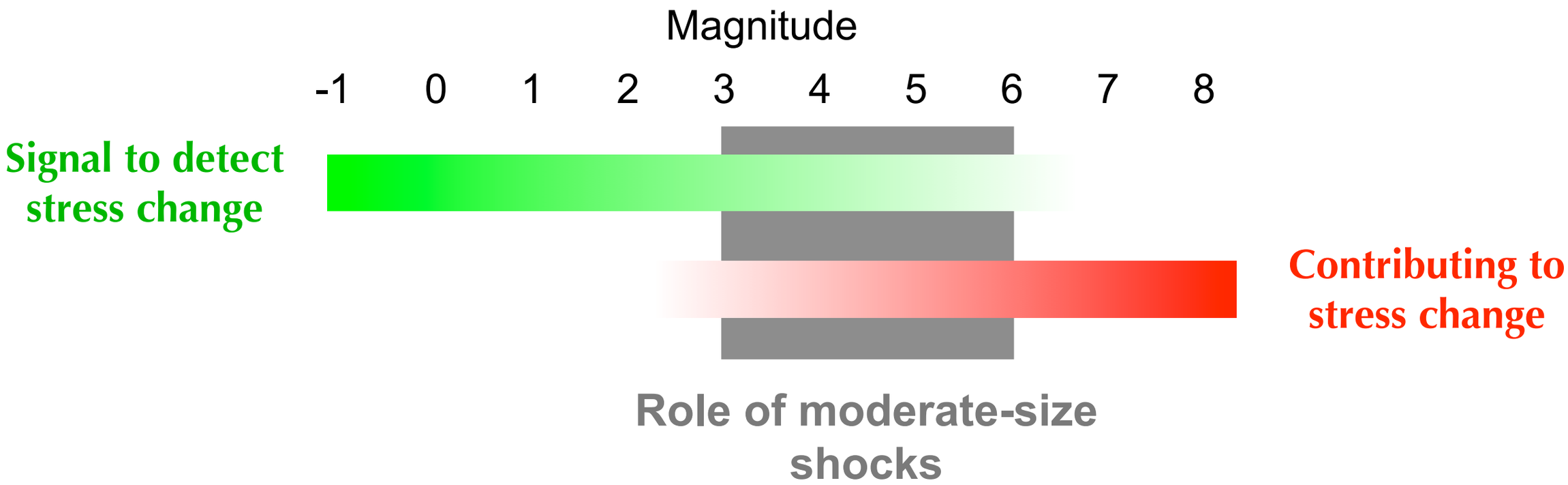
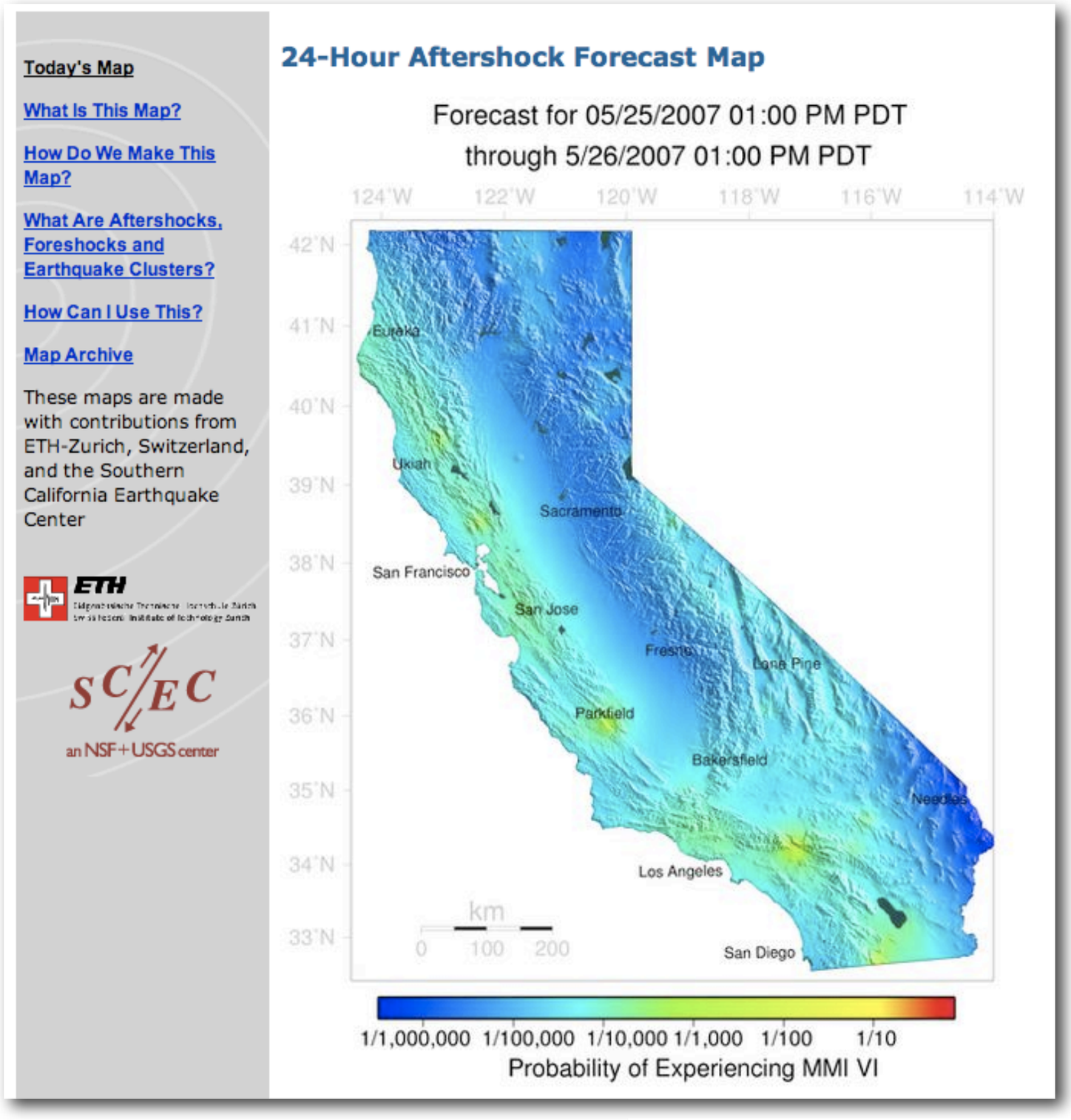
Role of multiple stress steps in earthquake triggering & application to near-real time aftershock forecasting



Shinji Toda

Active Fault Research Center, Geological Survey of Japan, AIST

Statistical aftershock (cluster) models consider small- to moderate-size shocks to raise local earthquake probability



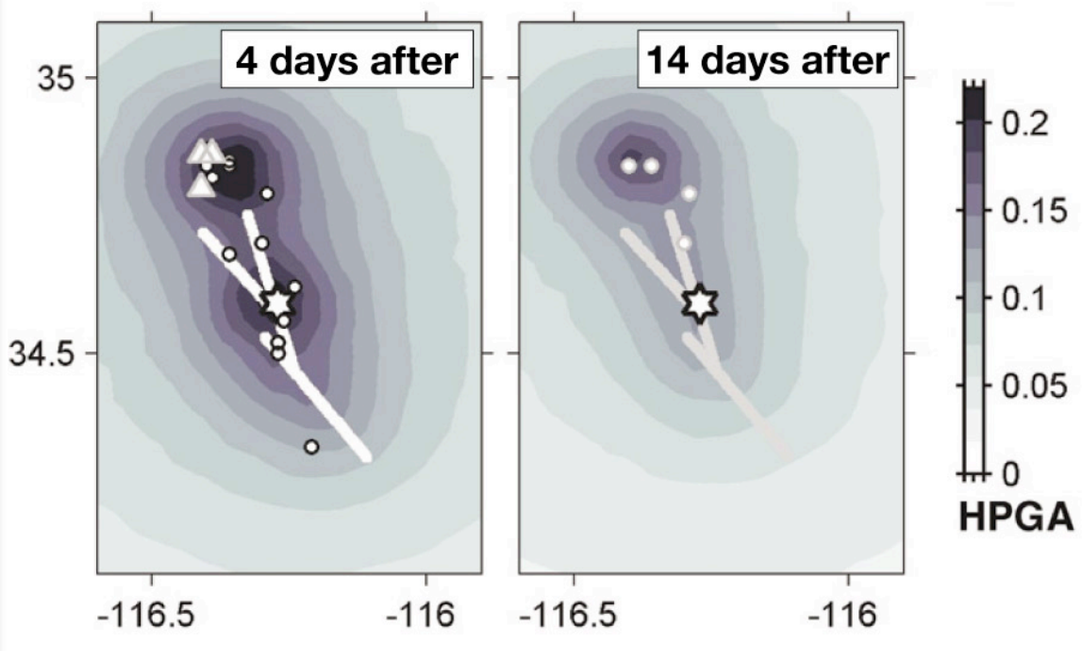
http://pasadena.wr.usgs.gov/step/

Gerstenberger et al., 2005

Any size of earthquake increases the chance of subsequent shock nearby

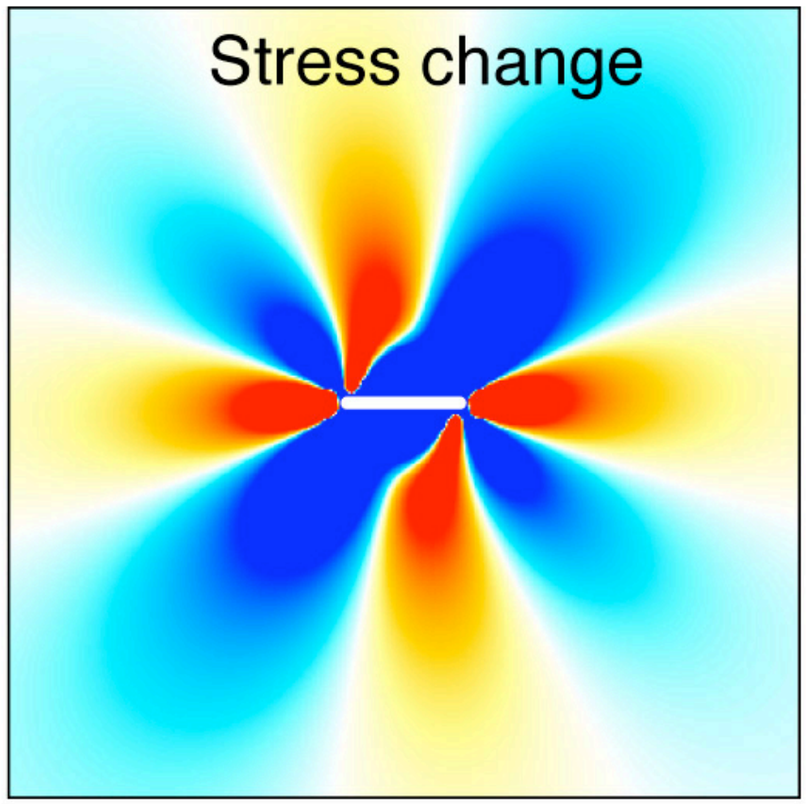
STEP, ETAS, ...

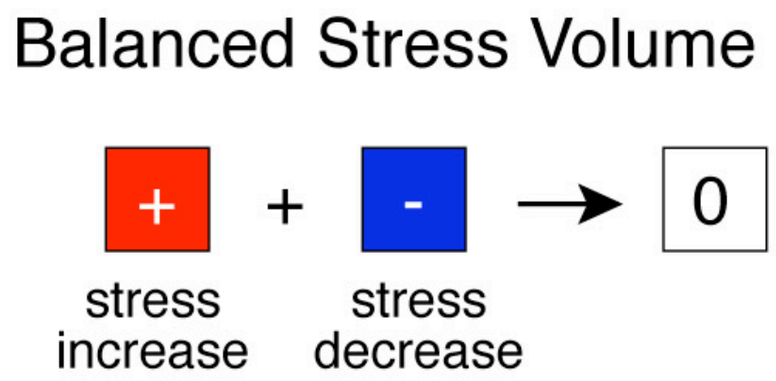
Wiemer et al., 2002

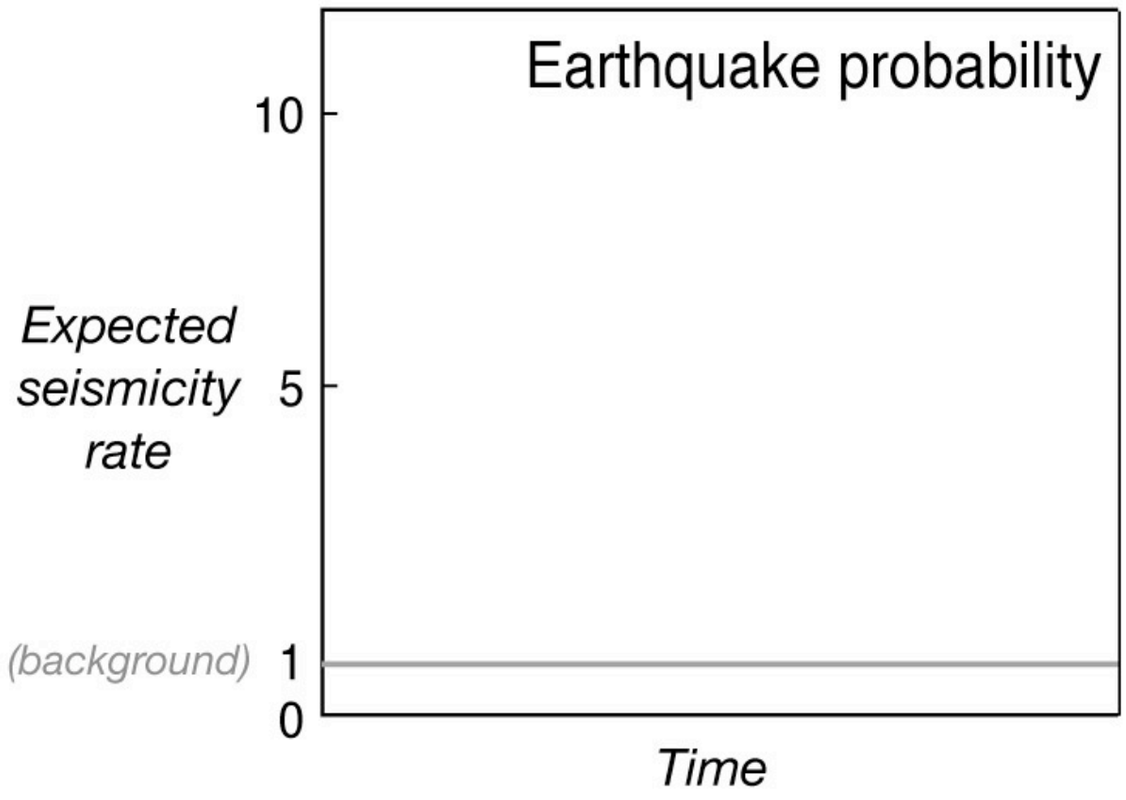


Probabilistic aftershock hazard map of Hector Mine region

Why a seismicity always gain?







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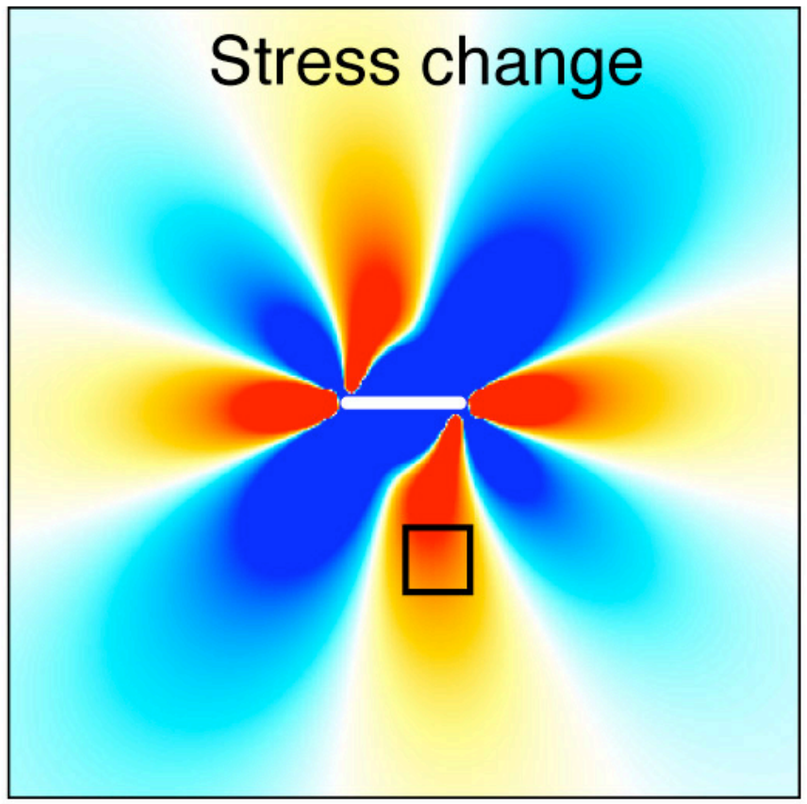
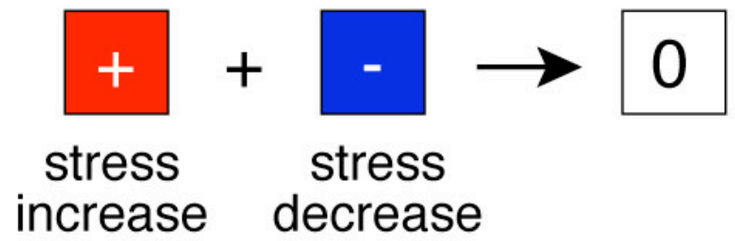
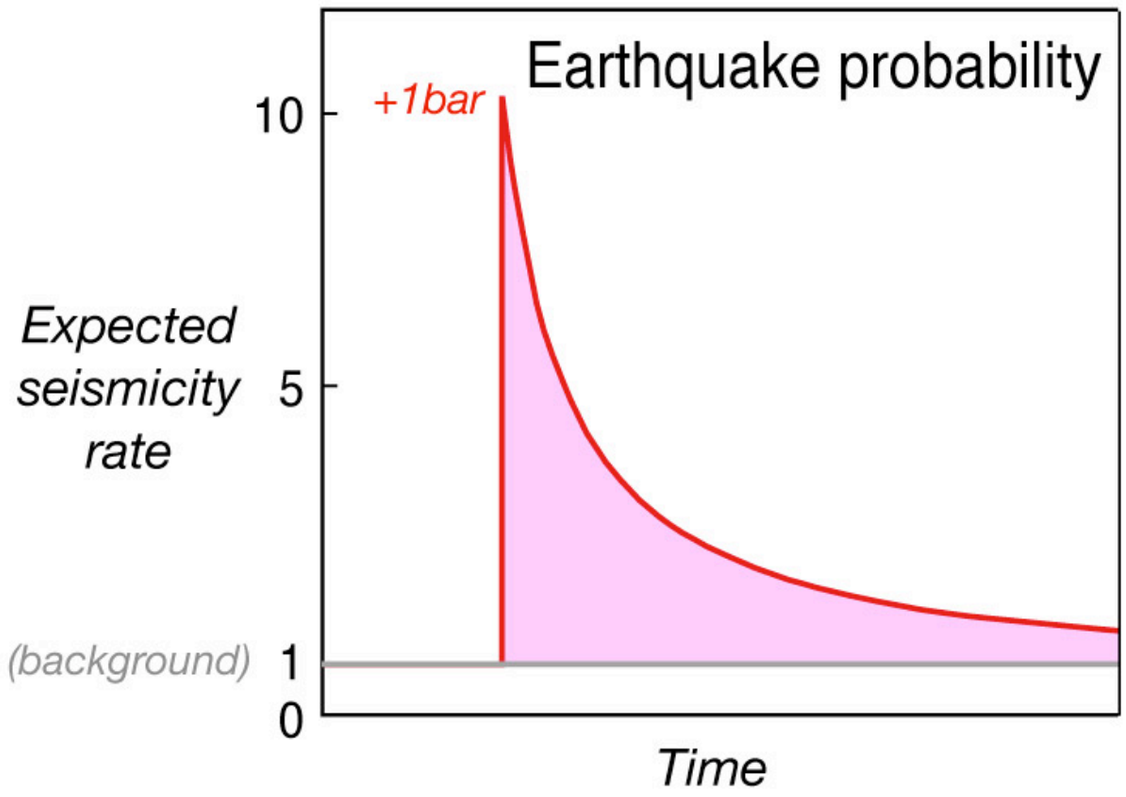
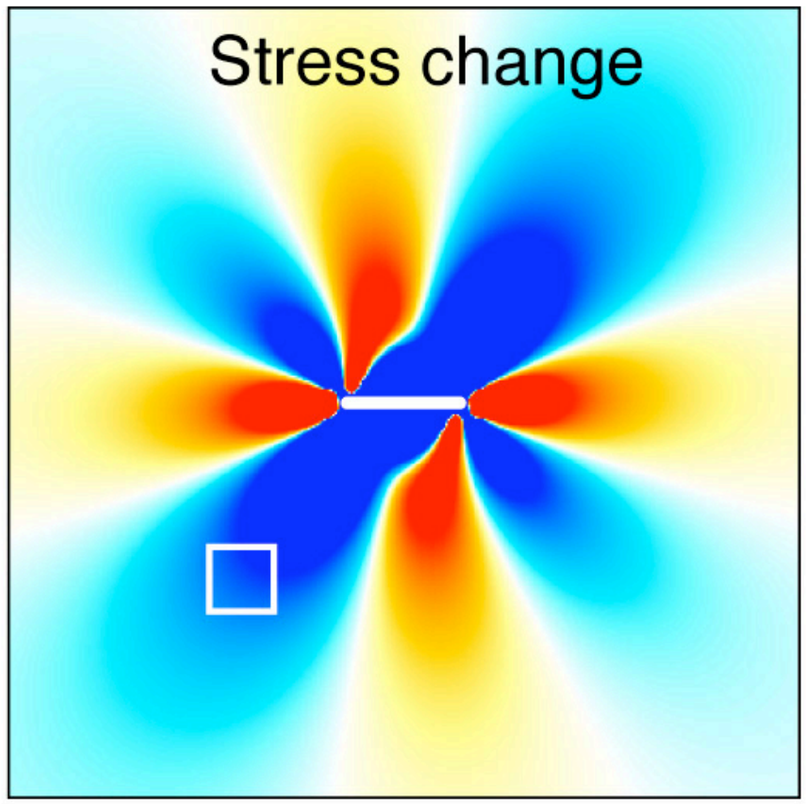


Balanced Stress Volume

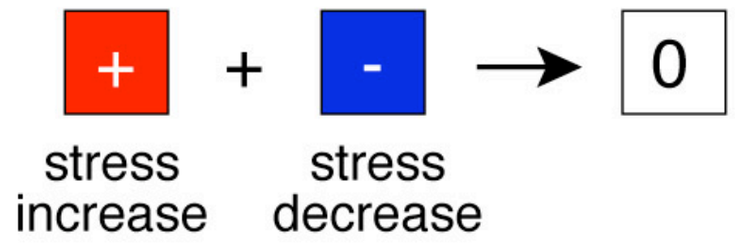


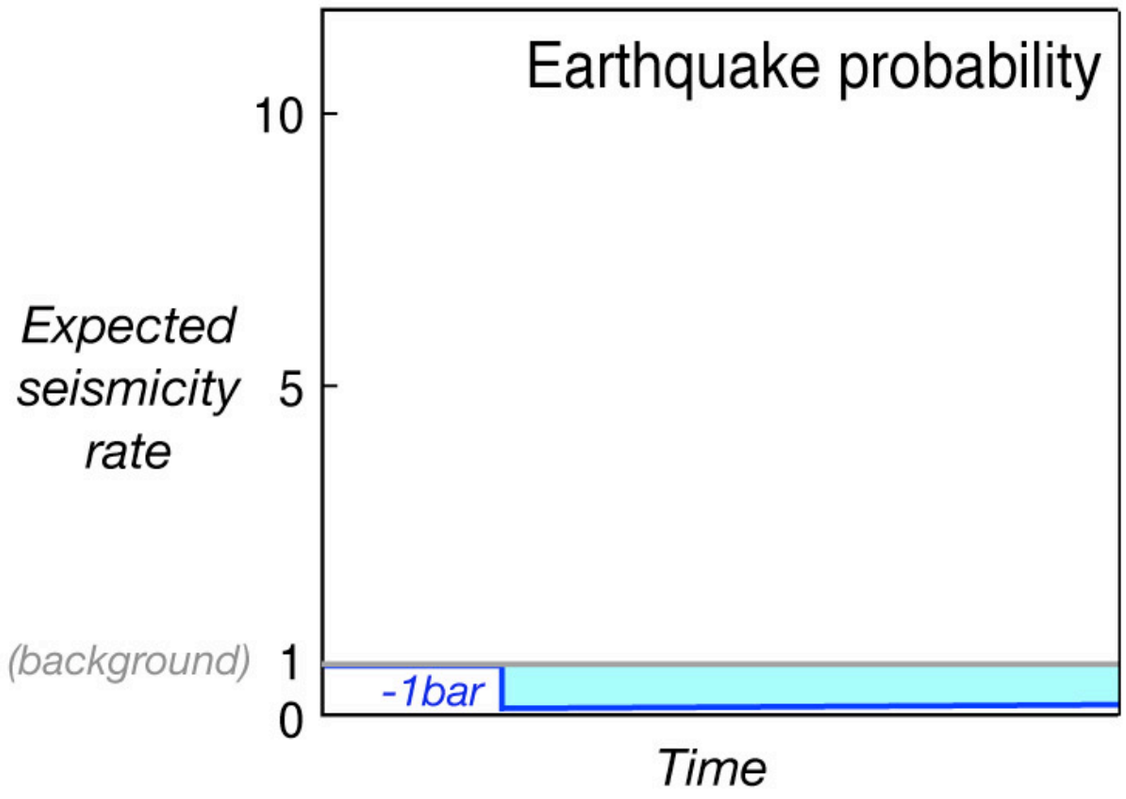




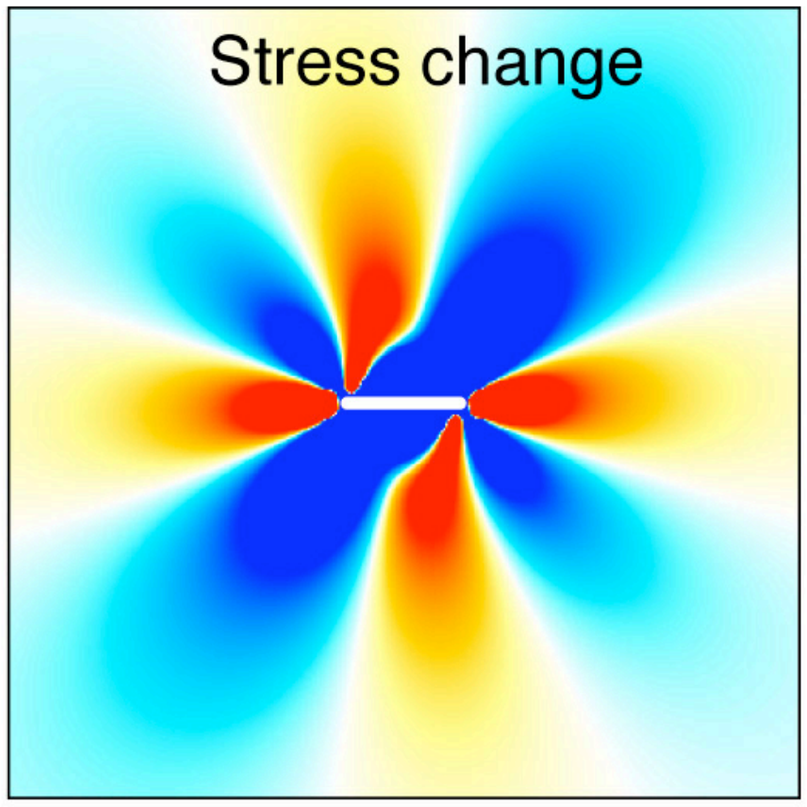
Why a seismicity always gain?

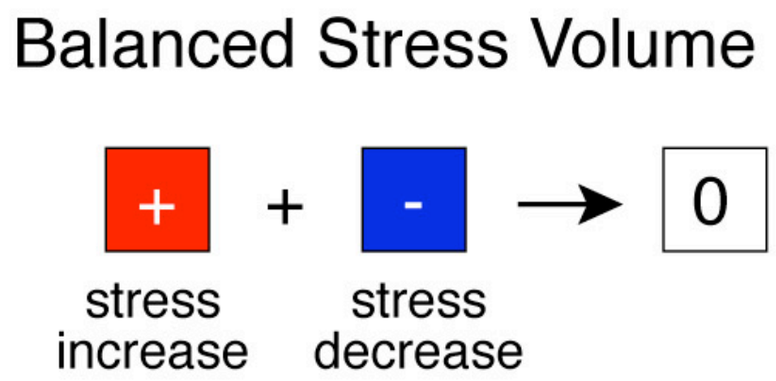
Balanced Stress Volume

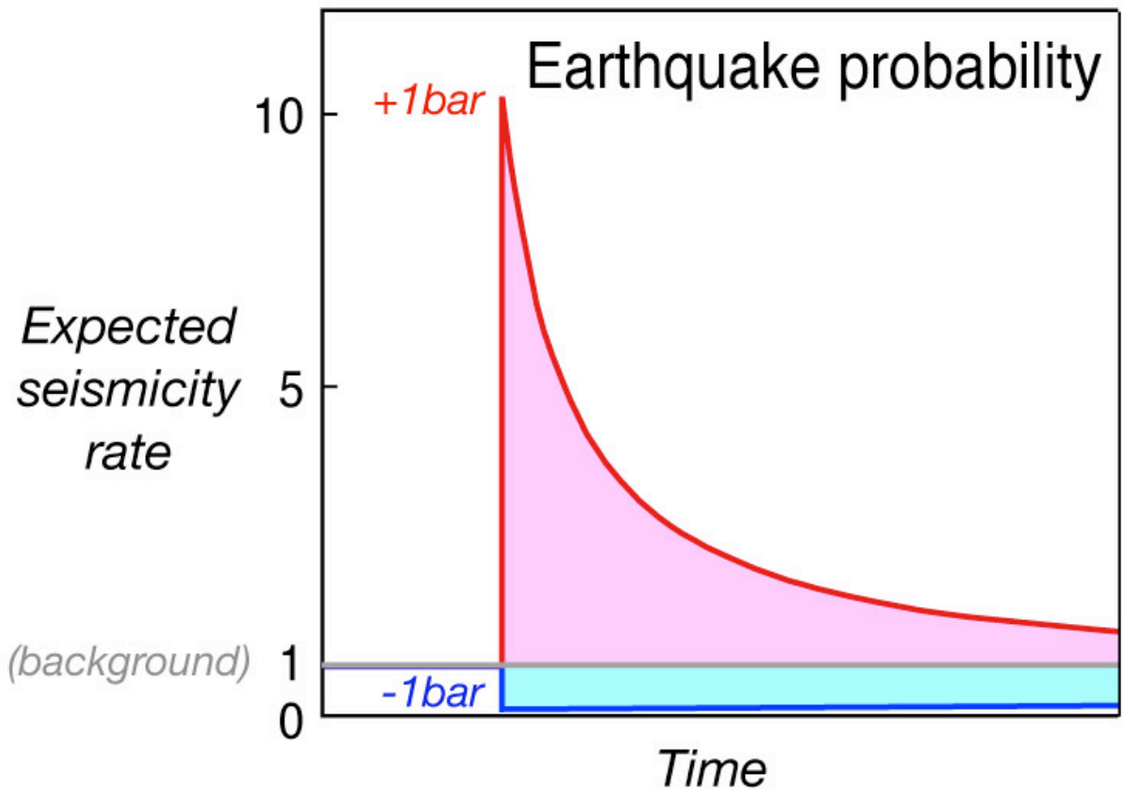


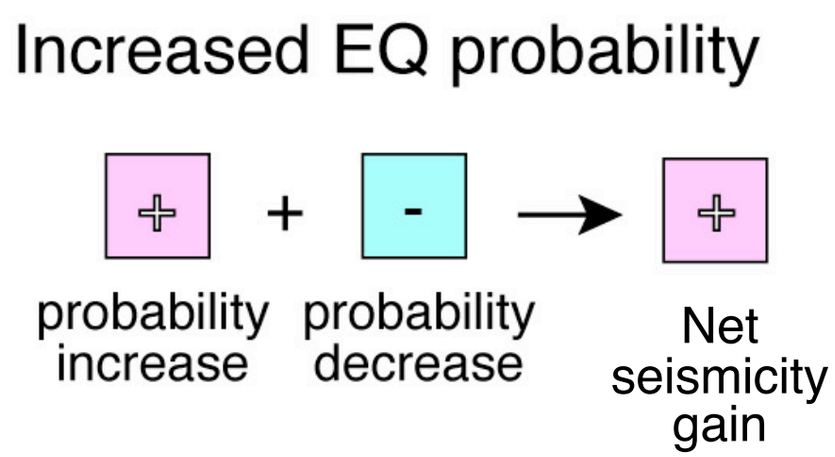


Why a seismicity always gain?









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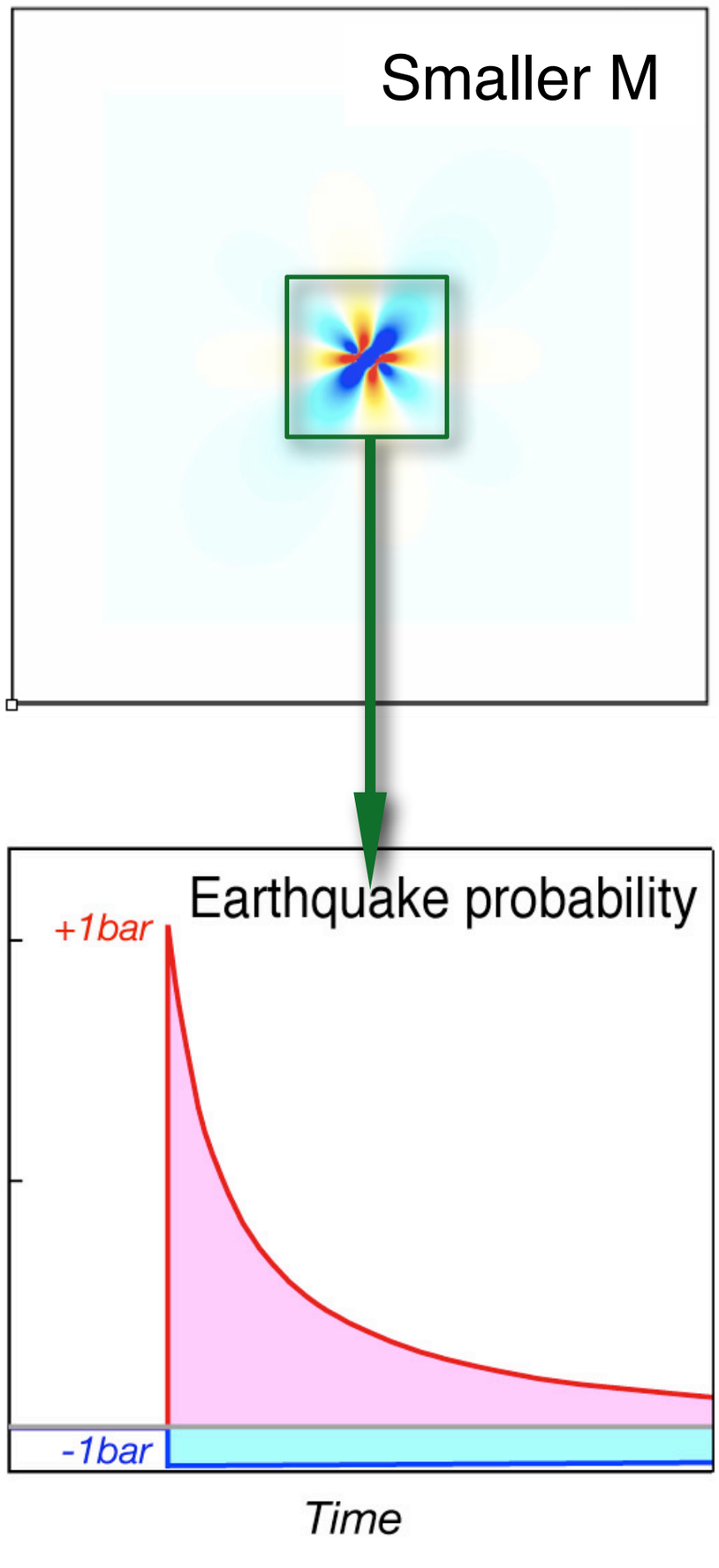
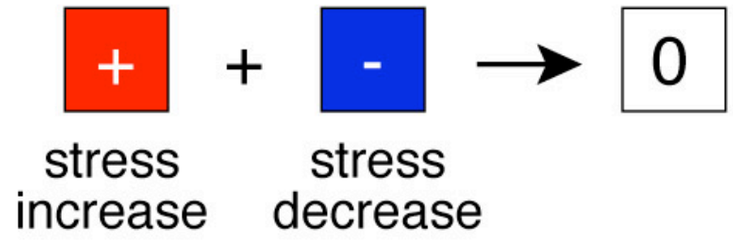
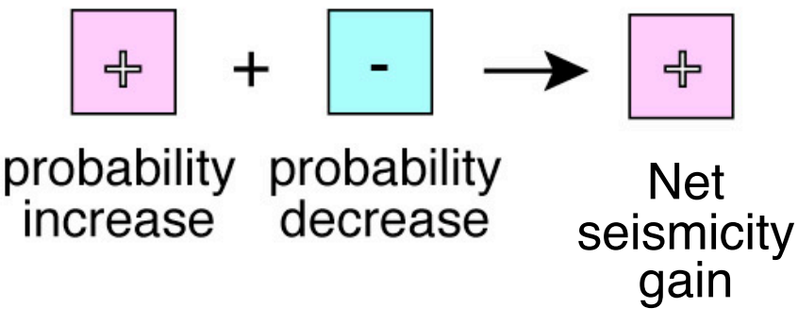


Balanced Stress Volume

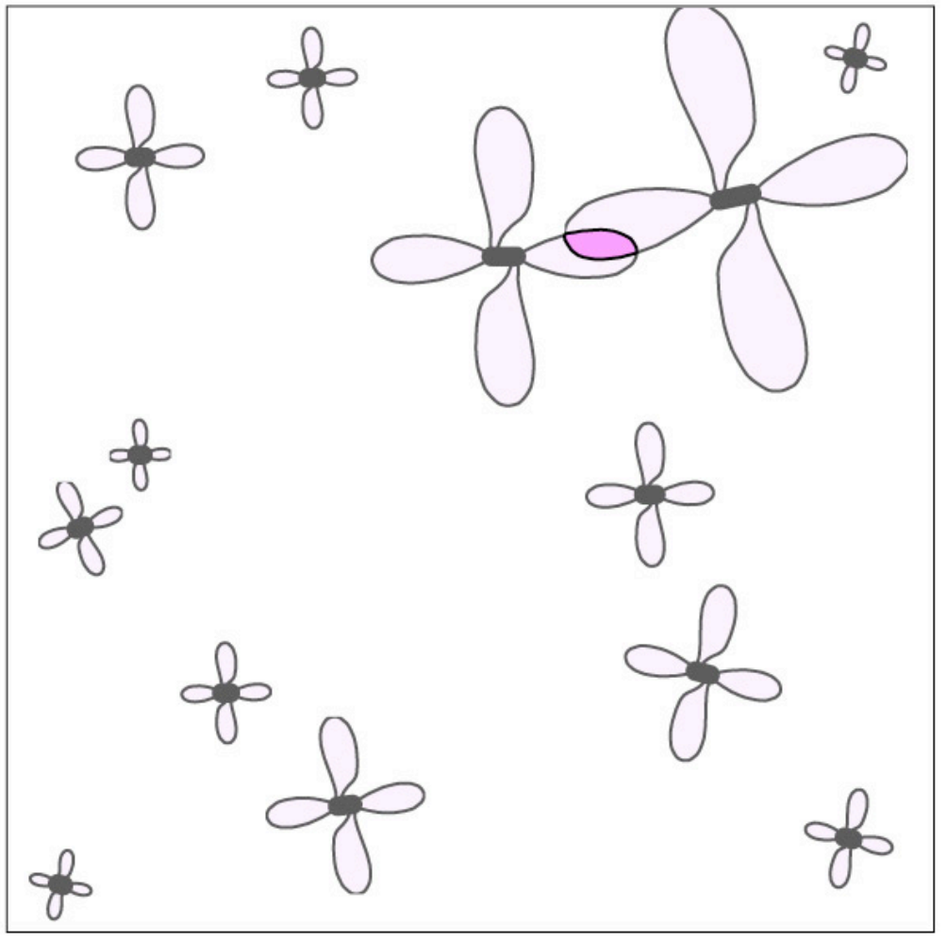


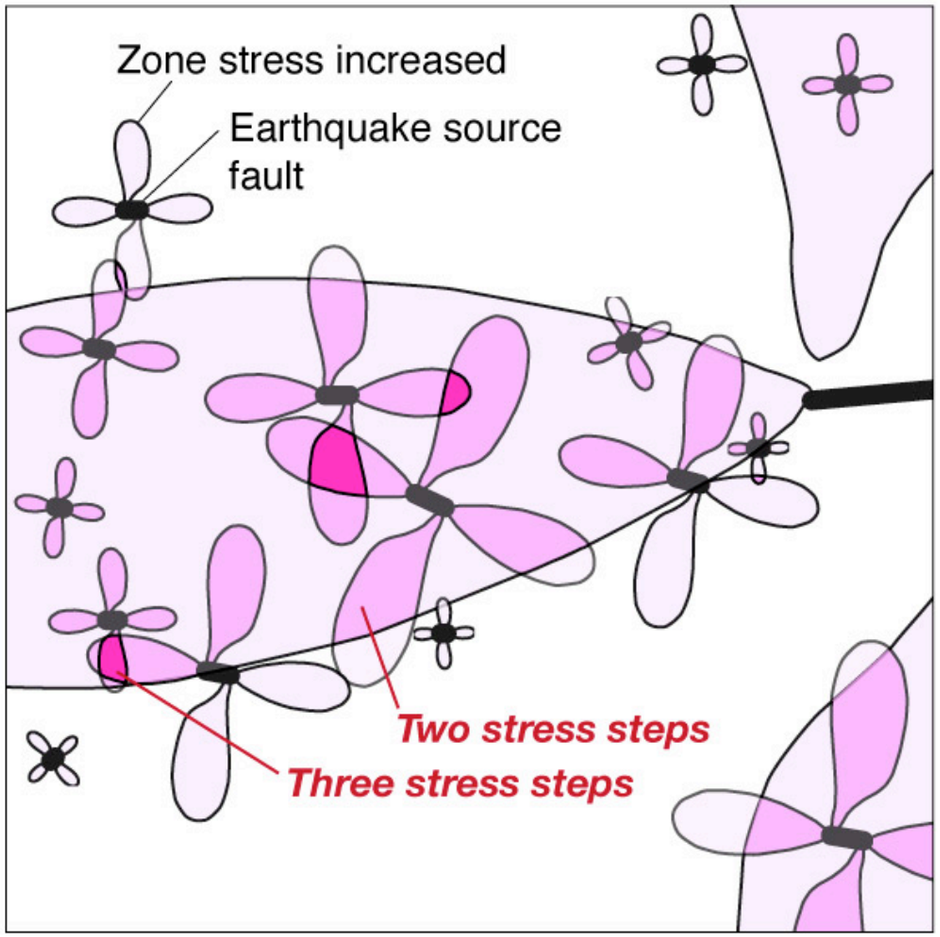
Any size of earthquake increases the chance of subsequent shock nearby

Increased EQ probability



Multiple stress steps are rare in background seismicity (left), but are common after a major shock (right)





Earthquake swarm may also cause such short term multiple stress steps

How do we model the seismicity evolution given multiple stress steps?

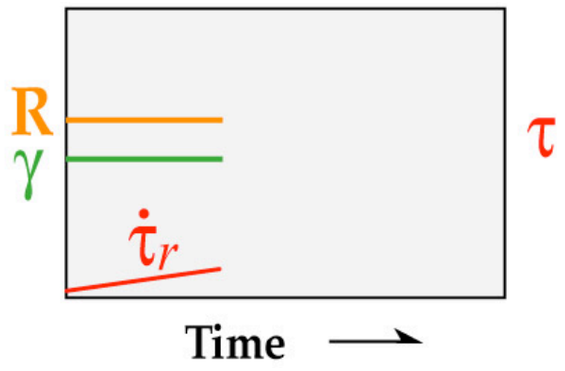
Seismicity rate

of *Dieterich* [1994]

$$R_n = \frac{r}{\gamma_n \dot{\tau}_r}$$

Steady state (initial state variable)

$$\gamma_o = \frac{1}{\dot{\tau}_r}$$



$\dot{\tau}_r$	secular shear stressing rate	Δt	time increment used to recalculate γ
r	background seismicity rate	$A\sigma$	constitutive parameter times the normal stress
γ_n	state variable (n time steps)	$\Delta\tau$	Shear stress change (~Coulomb stress change)
γ_o	state variable at steady state		

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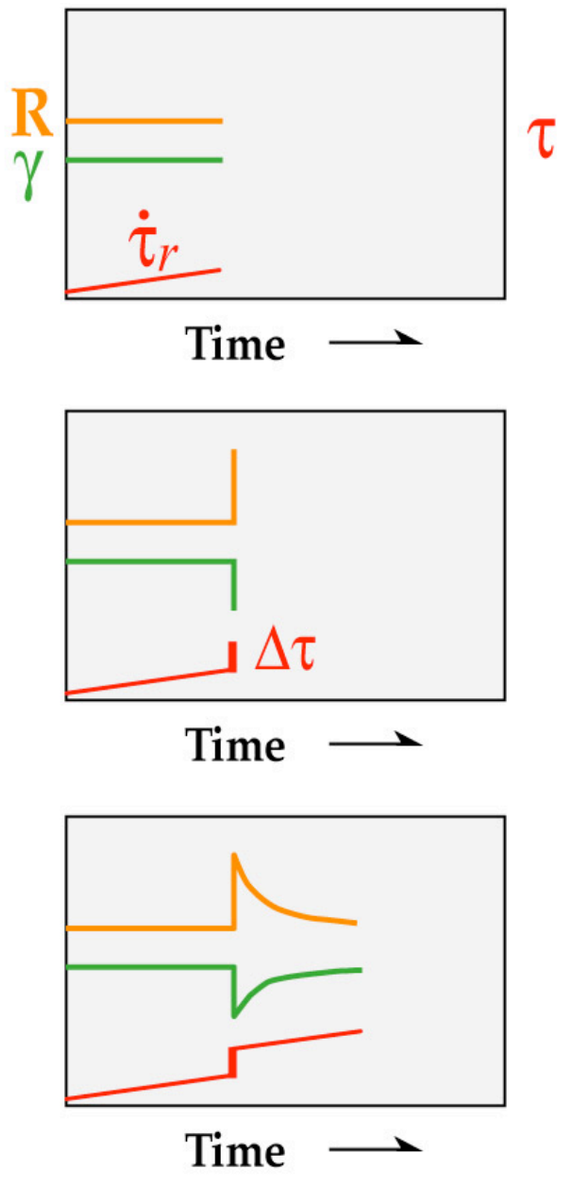
Drop / jump (evolution at a new **stress step**)

$$\gamma_n = \gamma_{n-1} \exp\left(\frac{-\Delta\tau}{A\sigma}\right)$$

Decay (evolution with time after a stress step)

$$\gamma_{n+1} = \left[\gamma_n - \frac{1}{\dot{\tau}_r}\right] \exp\left[\frac{-\Delta t\ \dot{\tau}_r}{A\sigma}\right] + \frac{1}{\dot{\tau}_r}$$



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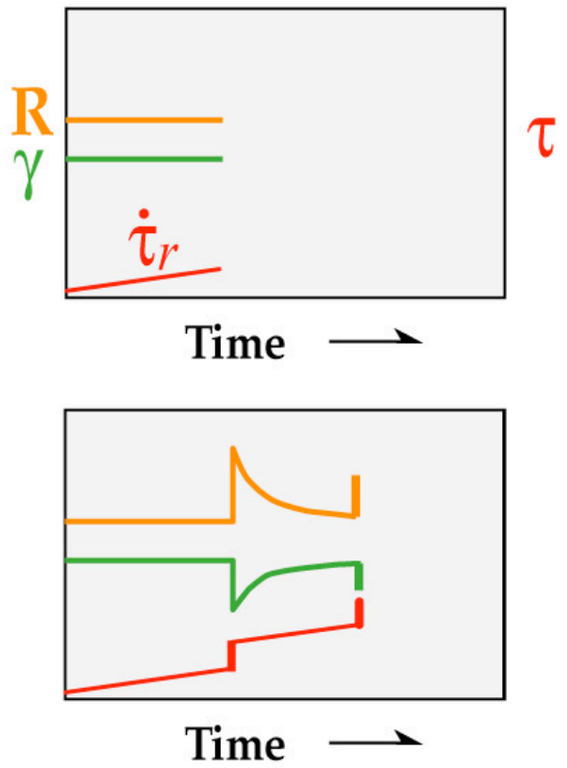

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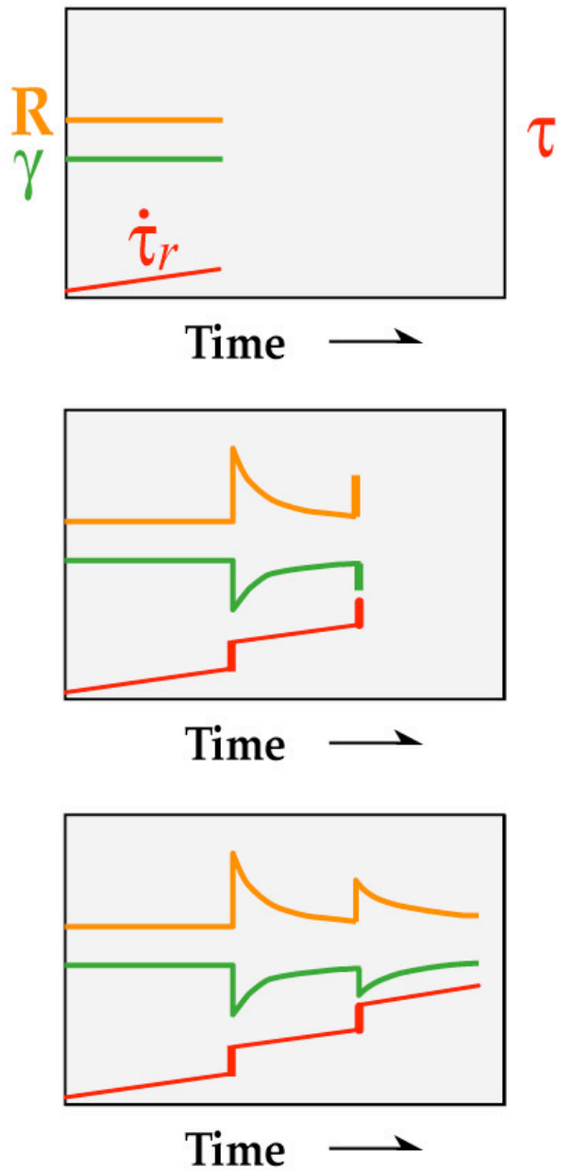

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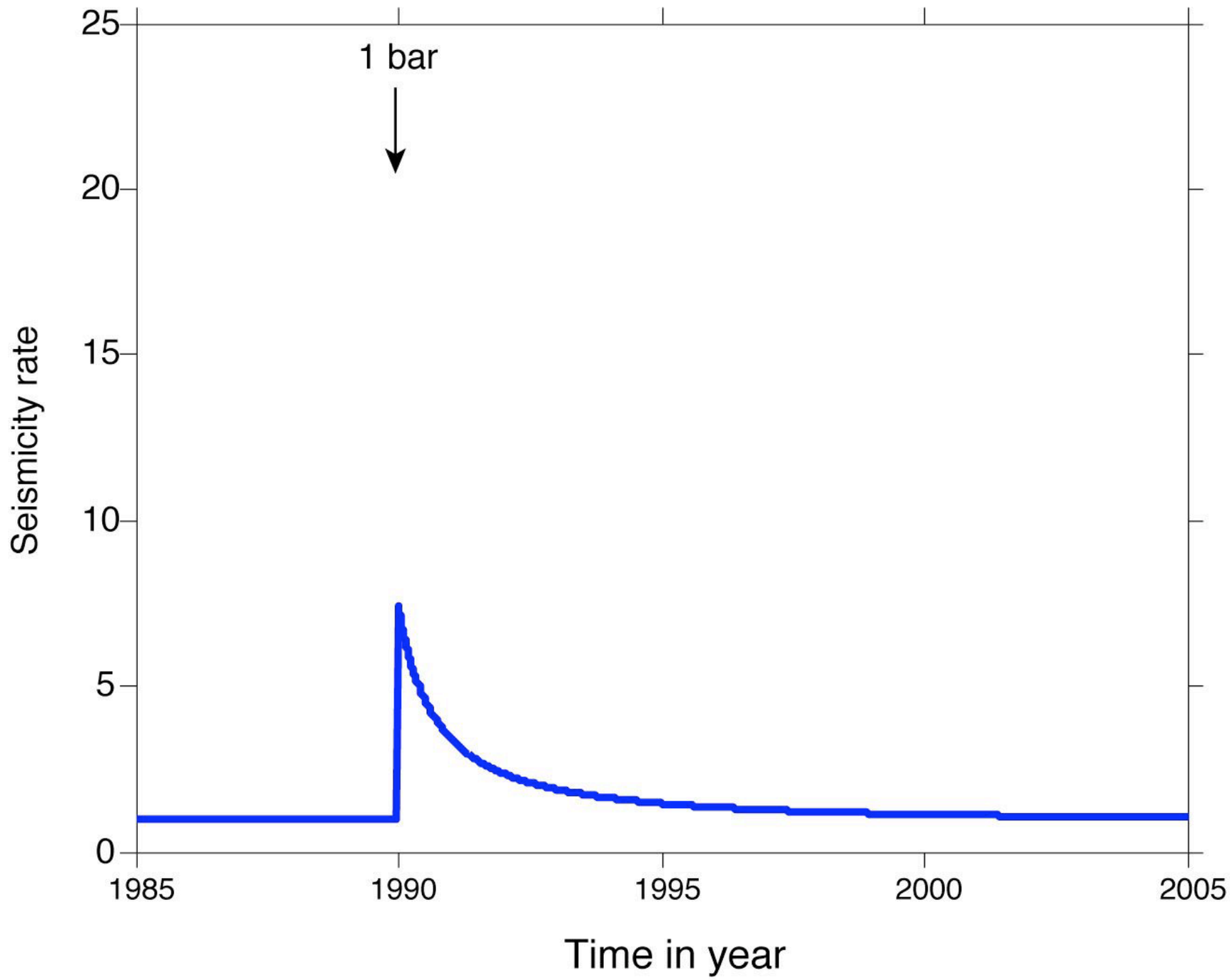
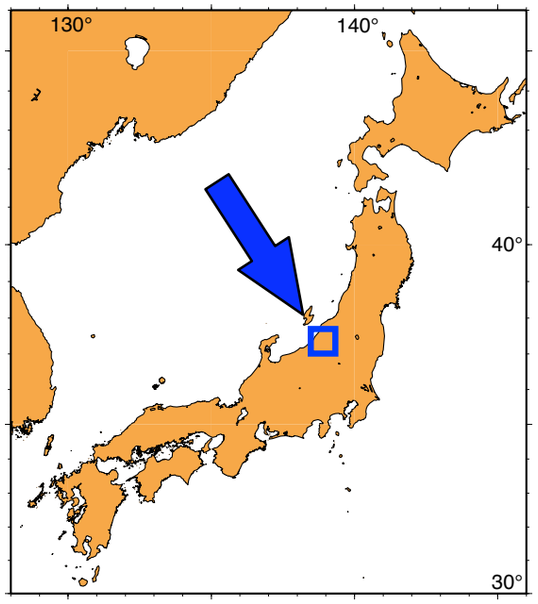
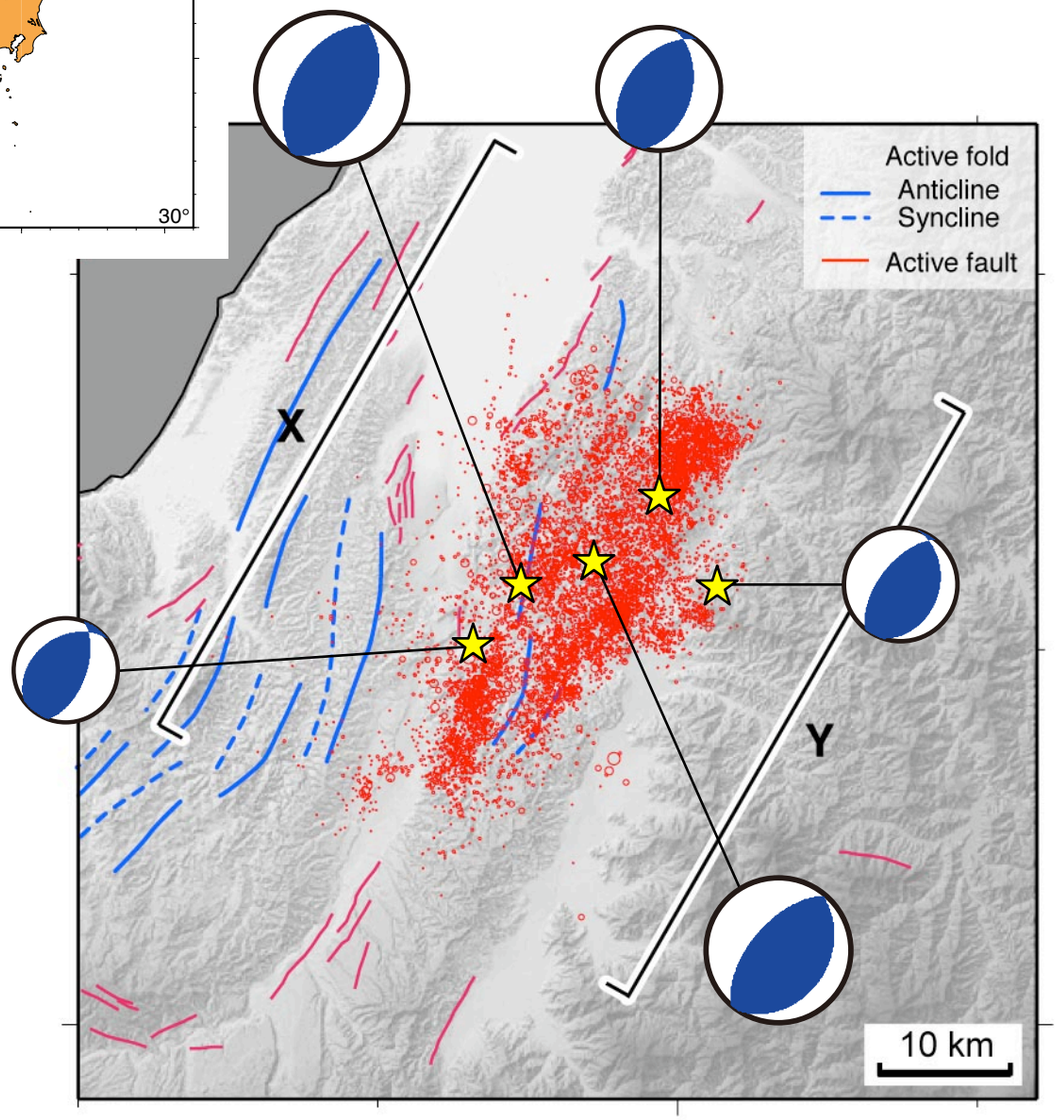
Timing of subsequent stress steps strongly influence local seismicity and possibly probability for a large one



Mainshock and successive large aftershocks triggered voluminous aftershocks



October 23, 2004 M 6.8
Niigata-ken Chuetsu
earthquake



M6.8 10/23 17:56 ---

↓ 7 min.

M6.3 10/23 18:03 ---

↓ 15 min.

M6.0 10/23 18:11 ---

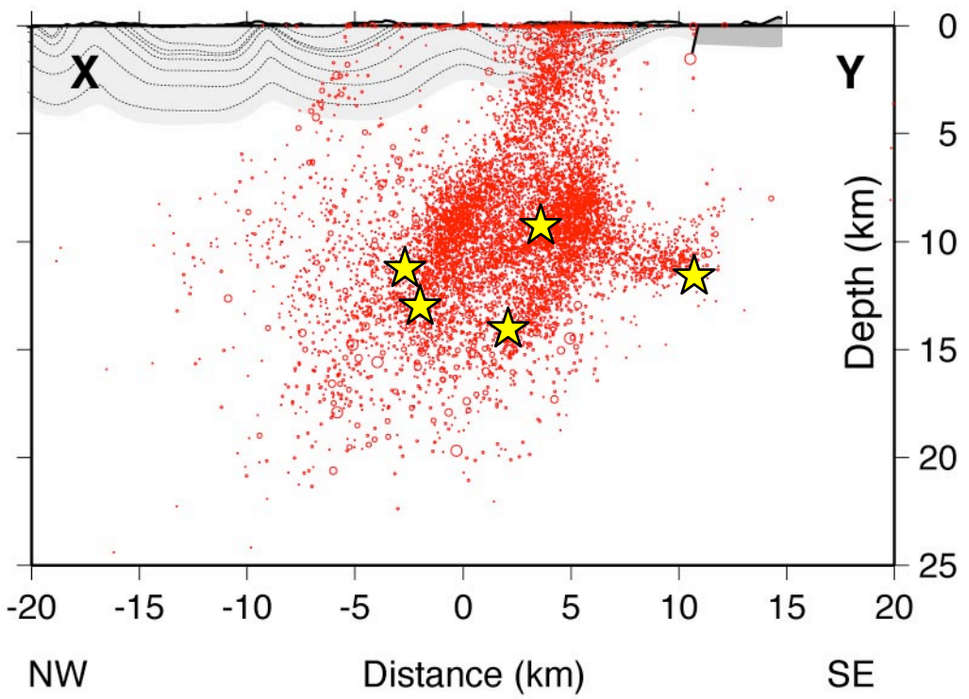
↓ 38 min.

M6.5 10/23 18:34 ---

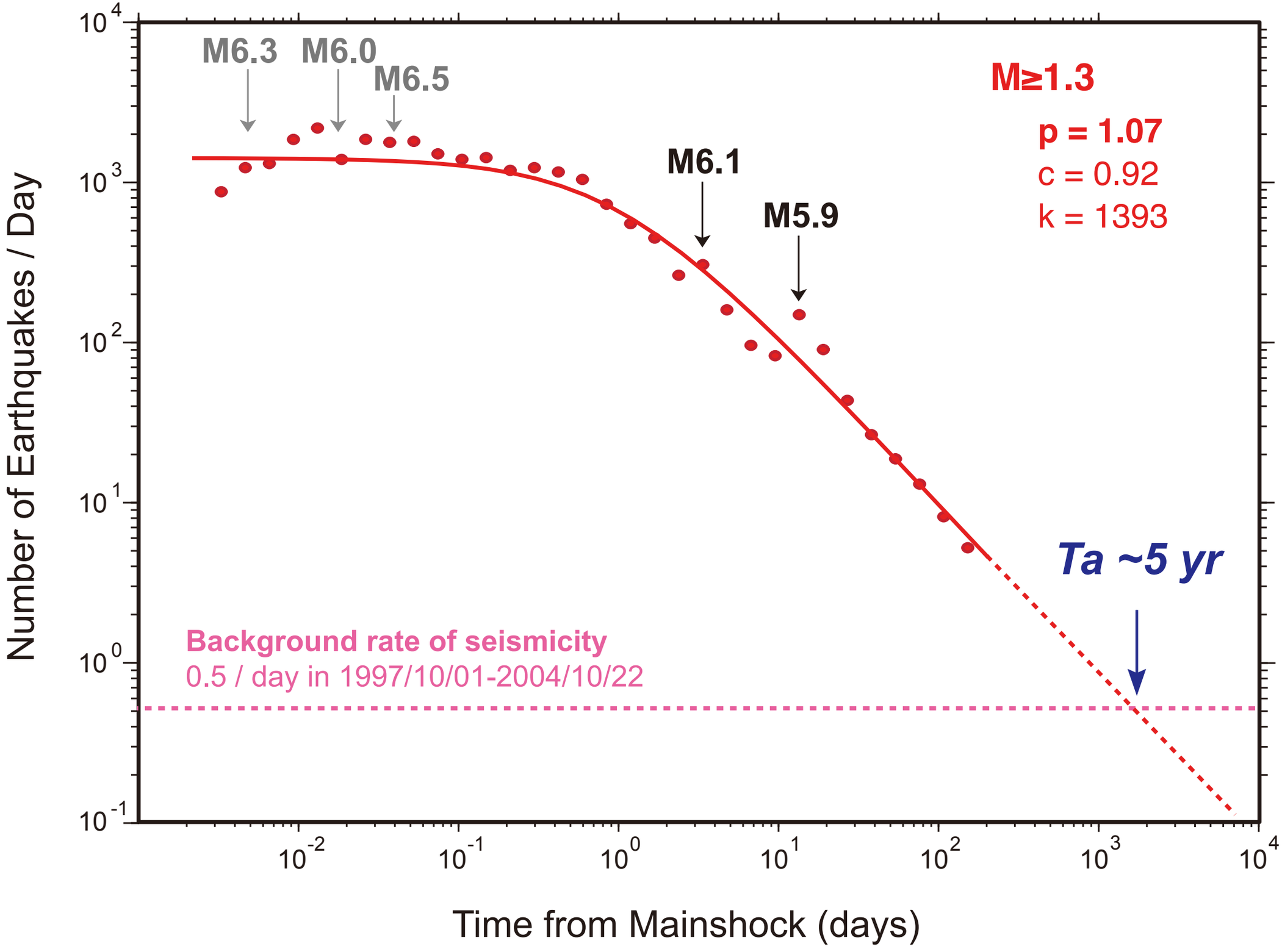
↓ 3 dy 17 hr

M6.1 10/27 10:40 ---

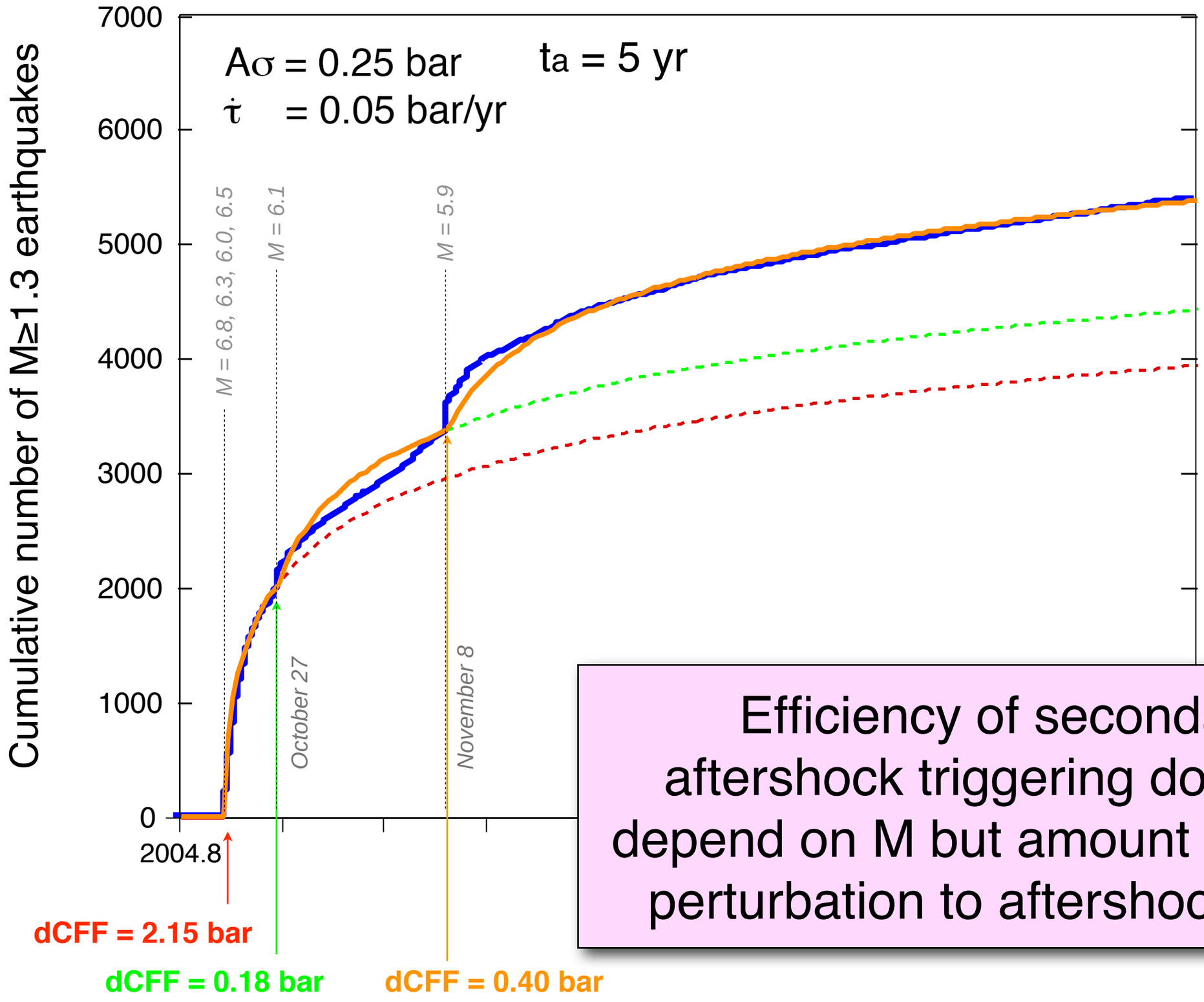
--- **2005**/03/31



Long C (~1 day) and bumpy decay process might be products of large aftershocks



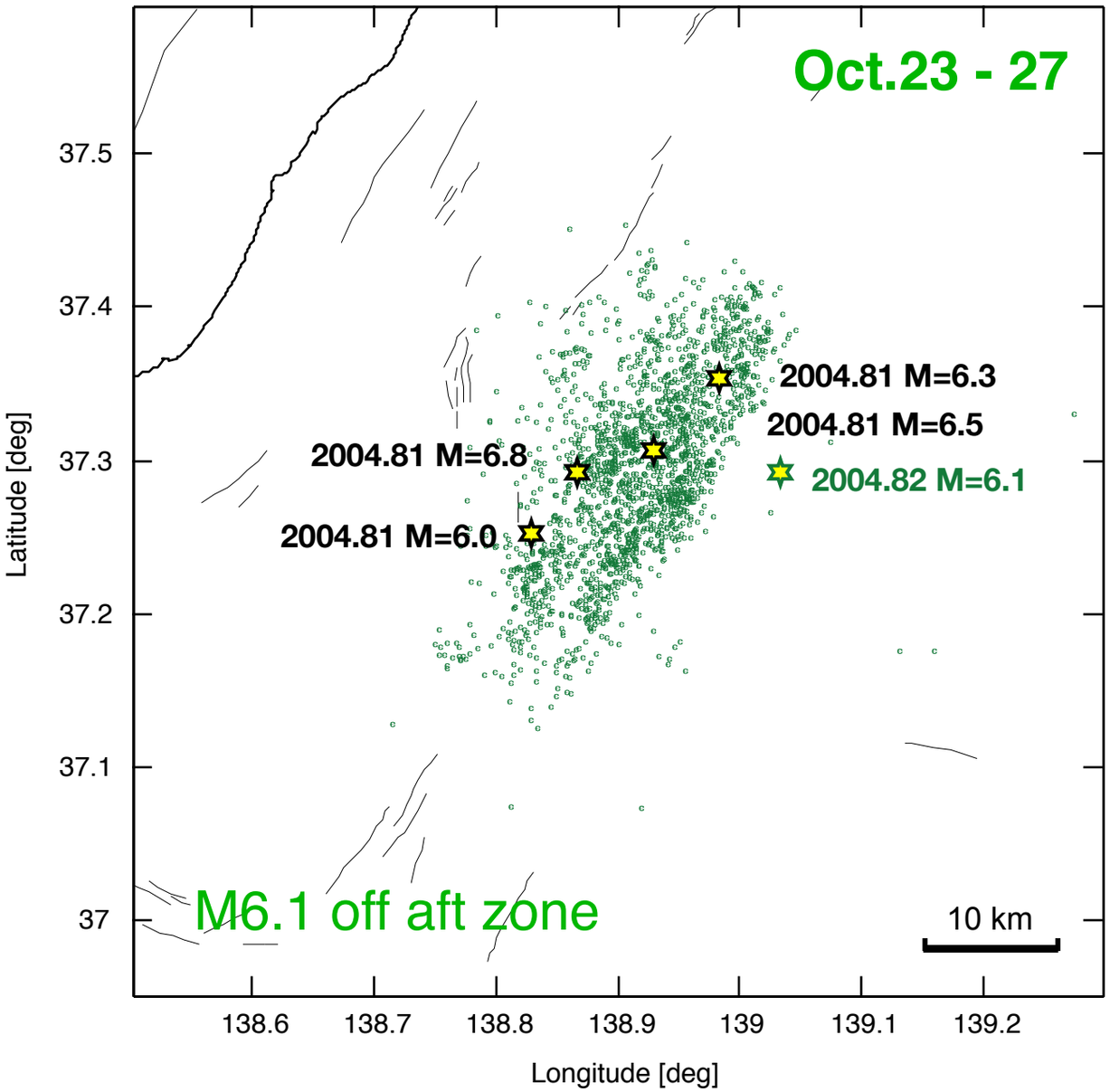
Huge aftershock sequence is a product of multiple stress steps



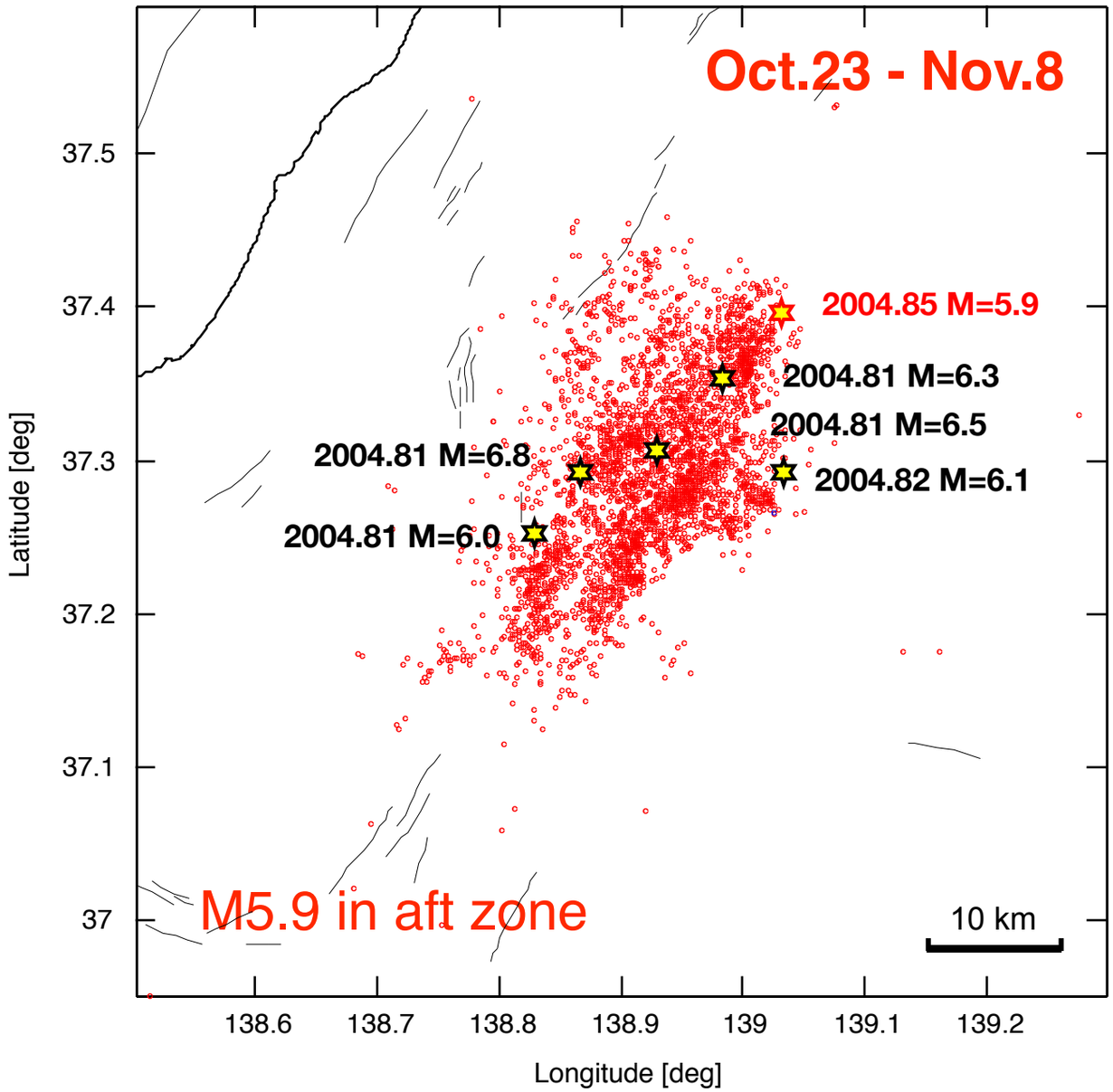
Efficiency of secondary aftershock triggering does not depend on M but amount of stress perturbation to aftershock zone

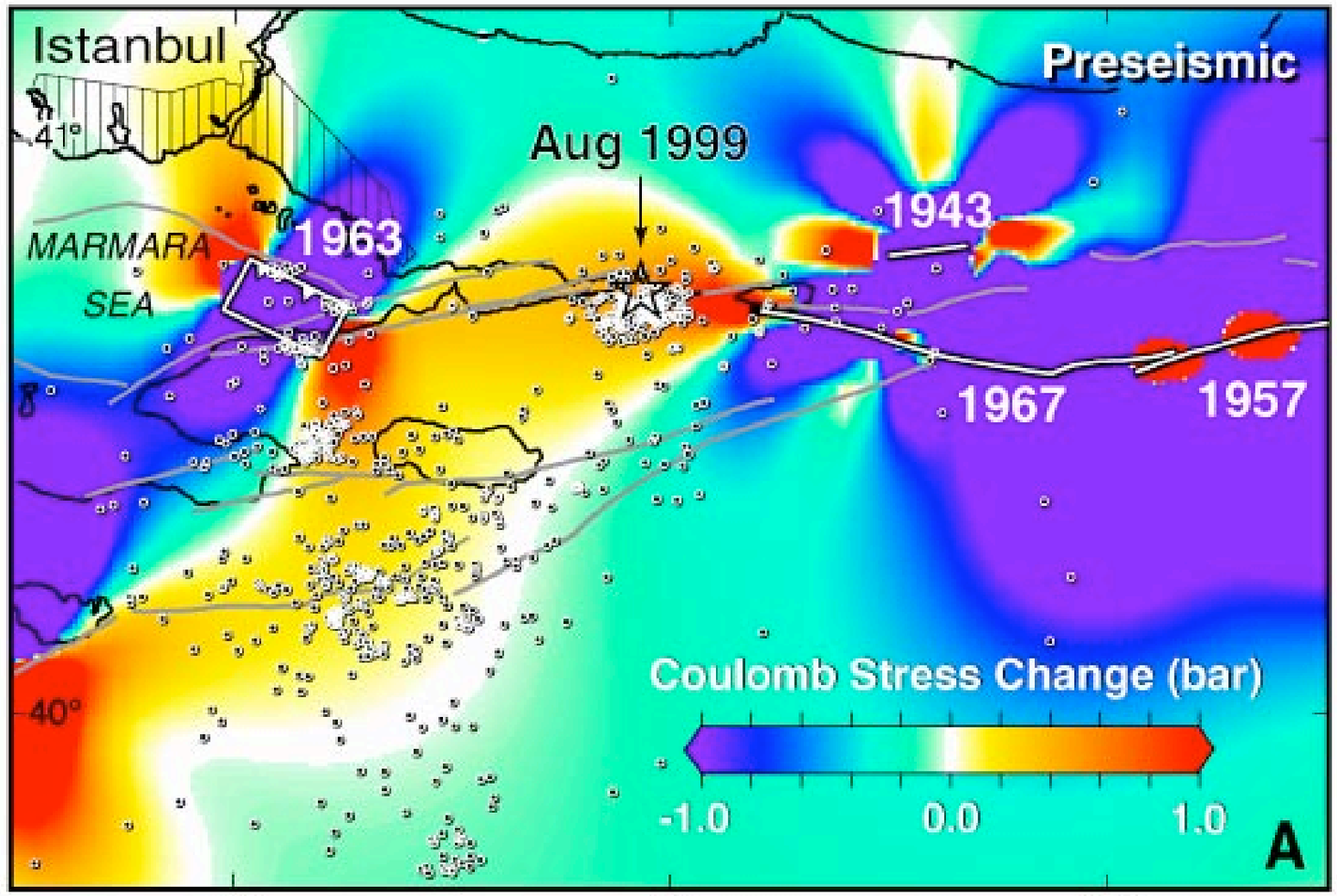
Impact of stress change on seismicity is not magnitude but relative location to the preceding aftershock zone

small impact



large impact



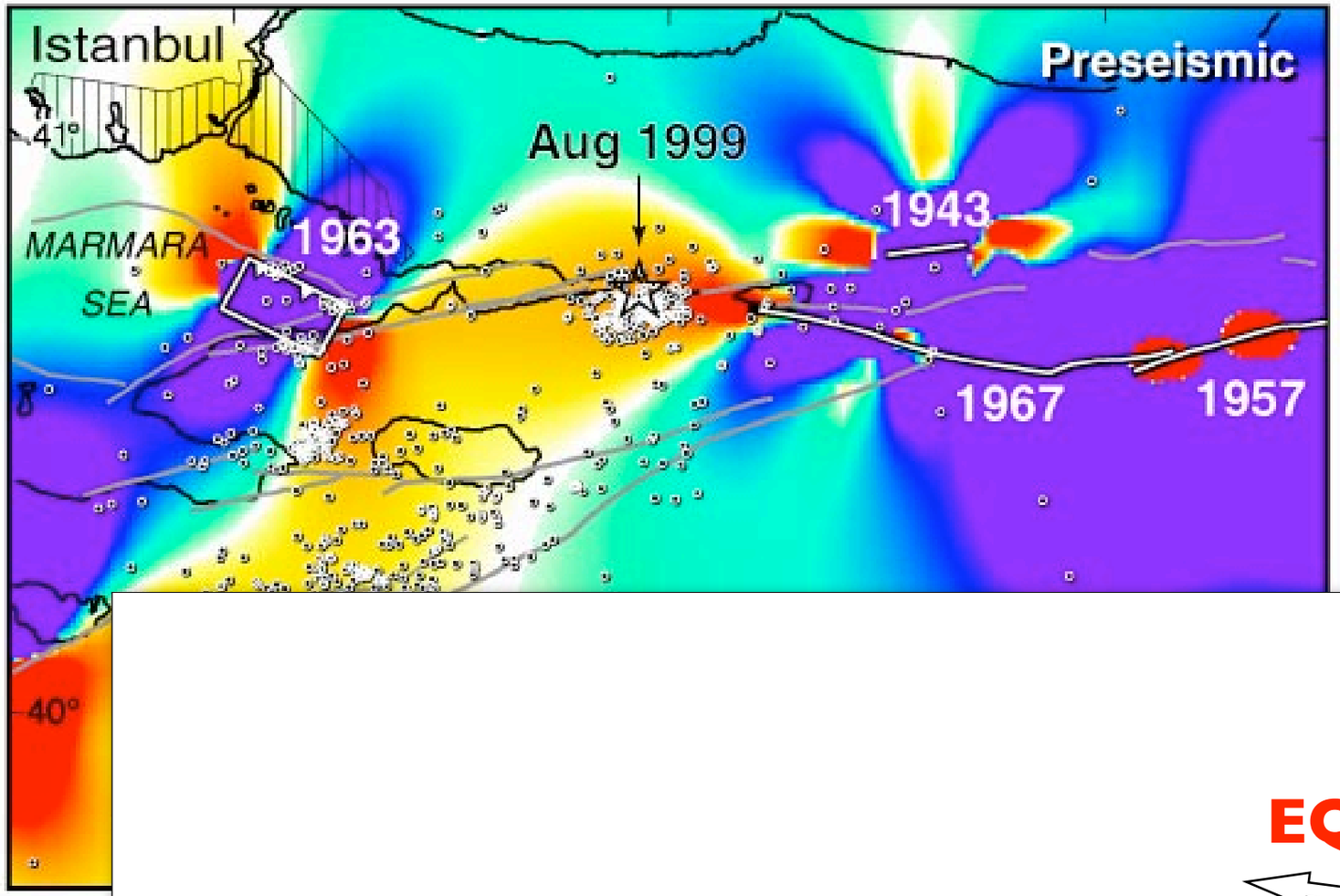


Parsons et al. (2000)

Spatio-temporal clustering is not only a signal of stress but also to increase chances of a subsequent large shock

◄ Before Aug. 1999 Izmit EQ

◄ Between Aug. 1999 Izmit EQ & Nov. 1999 Duzce EQ



Spatio-temporal clustering is not only a signal of stress but also to increase chances of a subsequent large shock

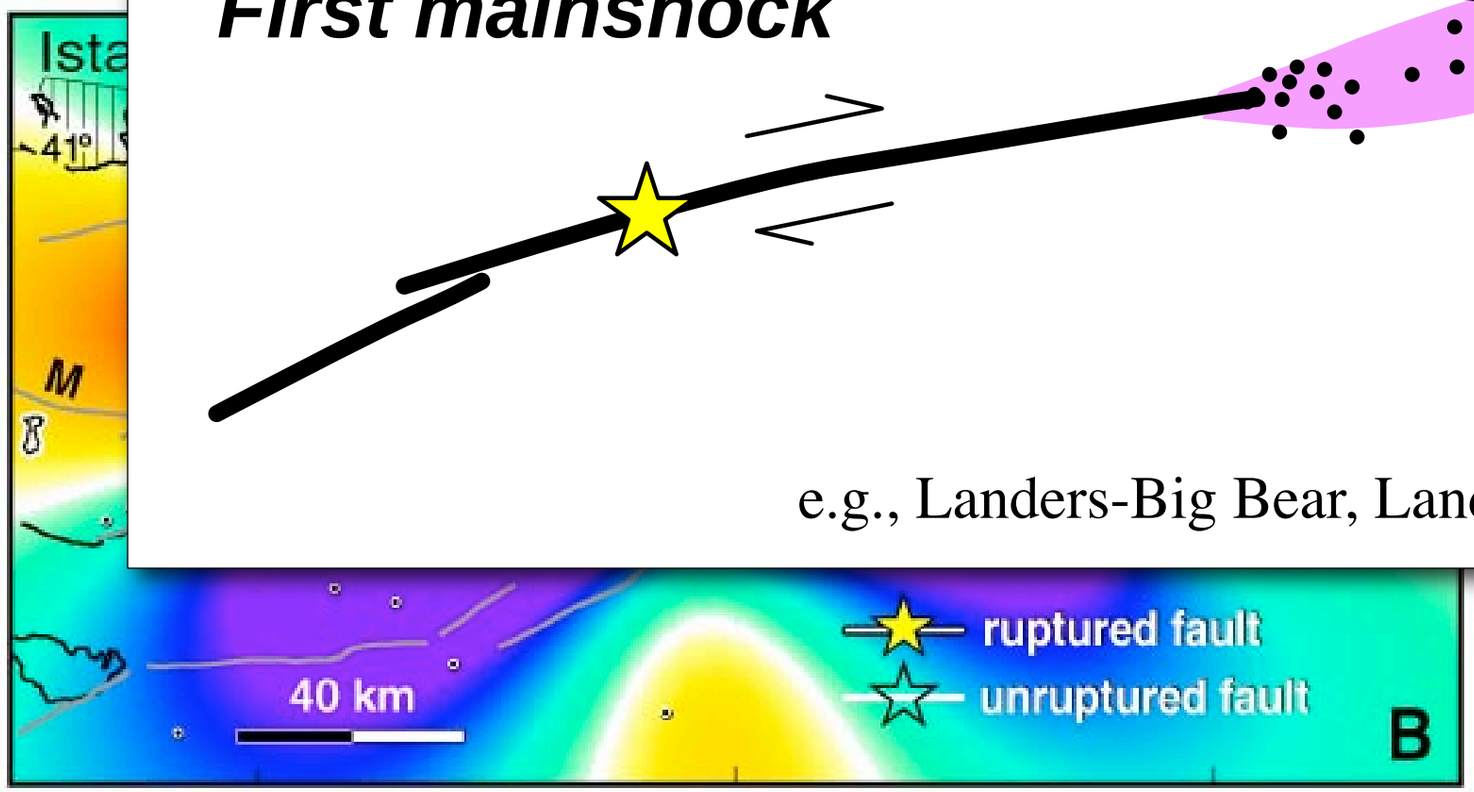
Second mainshock

EQ cluster

First mainshock

aseismic (~locked) asperity

e.g., Landers-Big Bear, Landers-Hector Mine, Ninana-Denali, etc.



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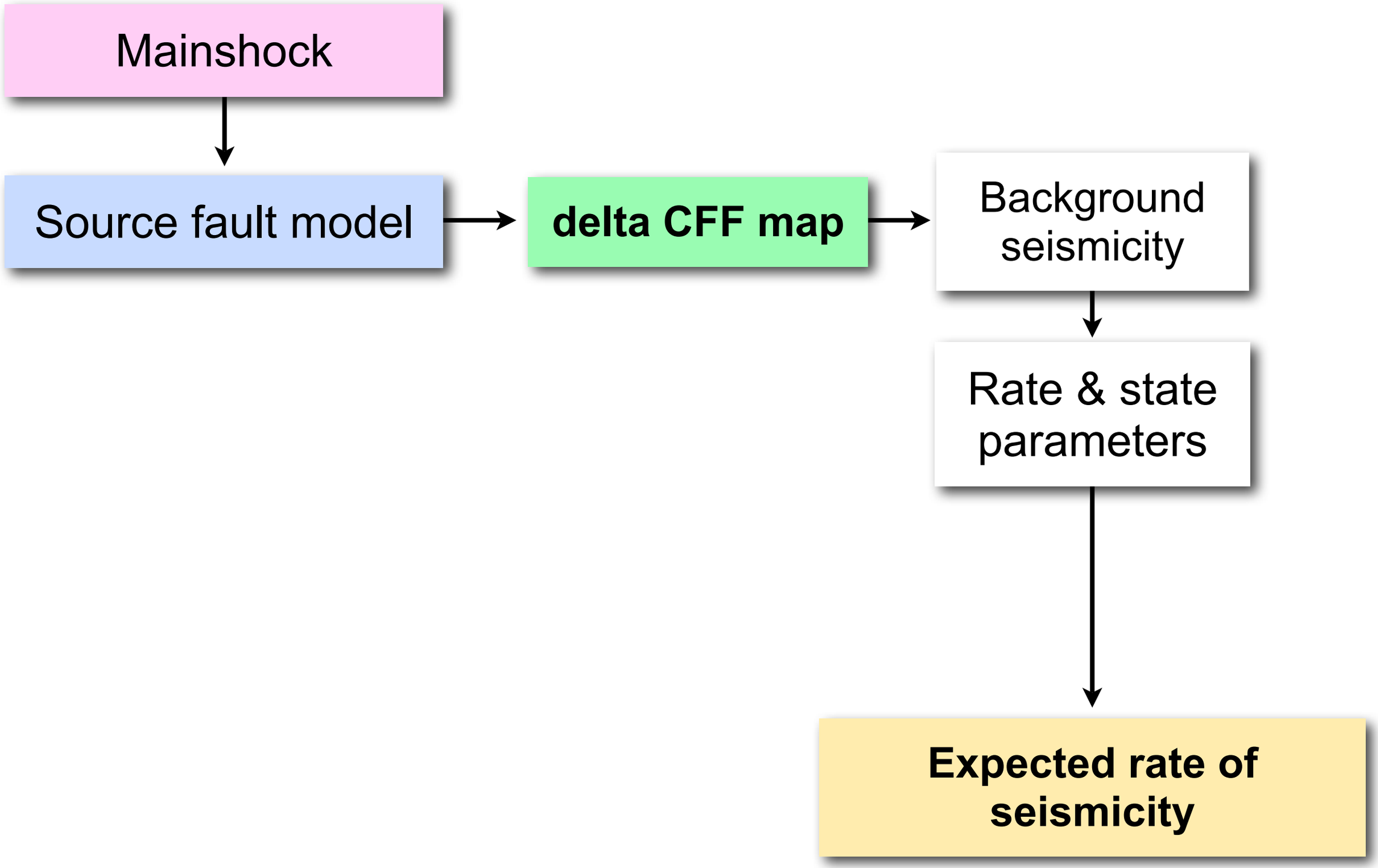
Parsons et al. (2000)

Procedure for near real time aftershock hazard assessment using Coulomb hypothesis



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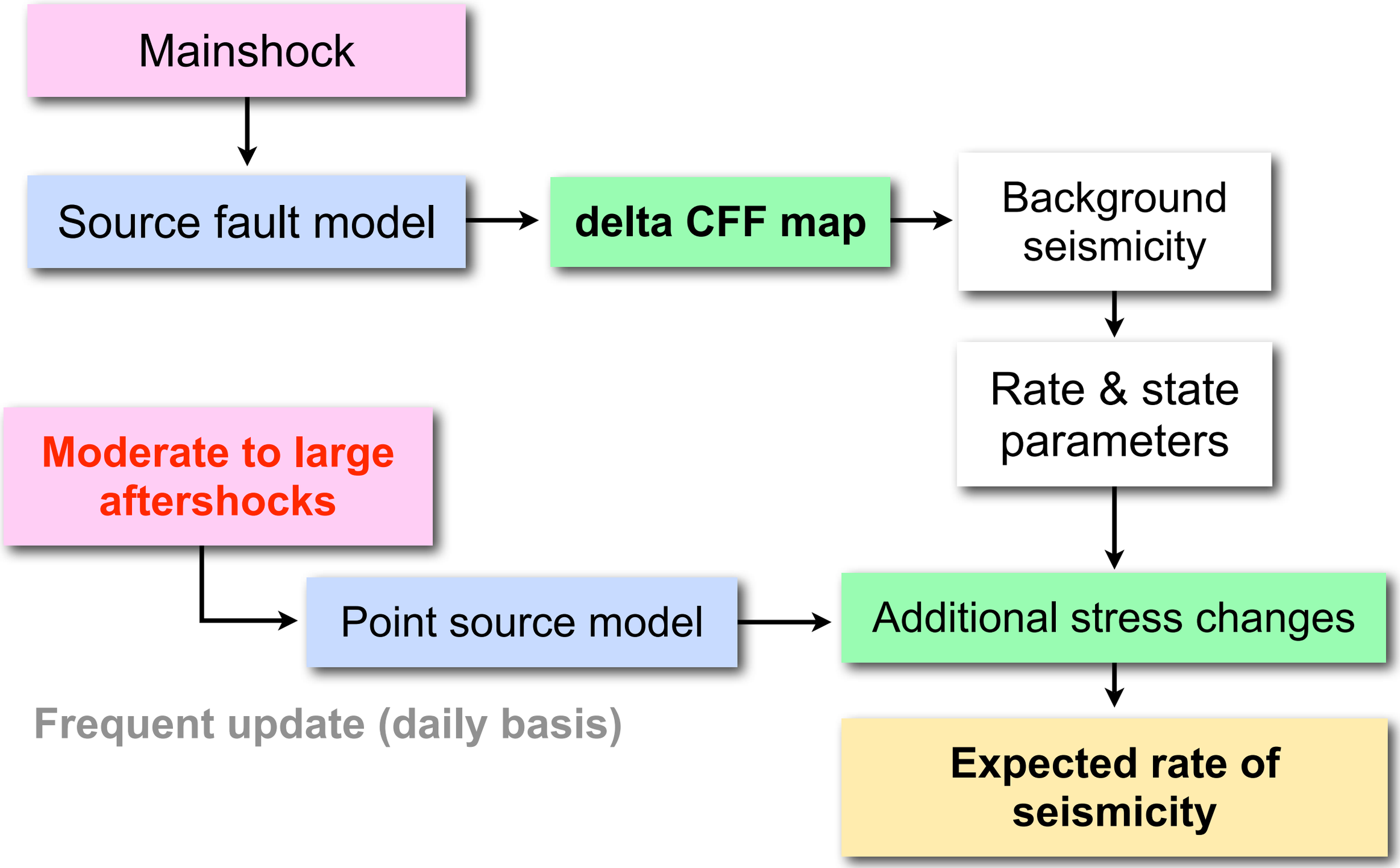
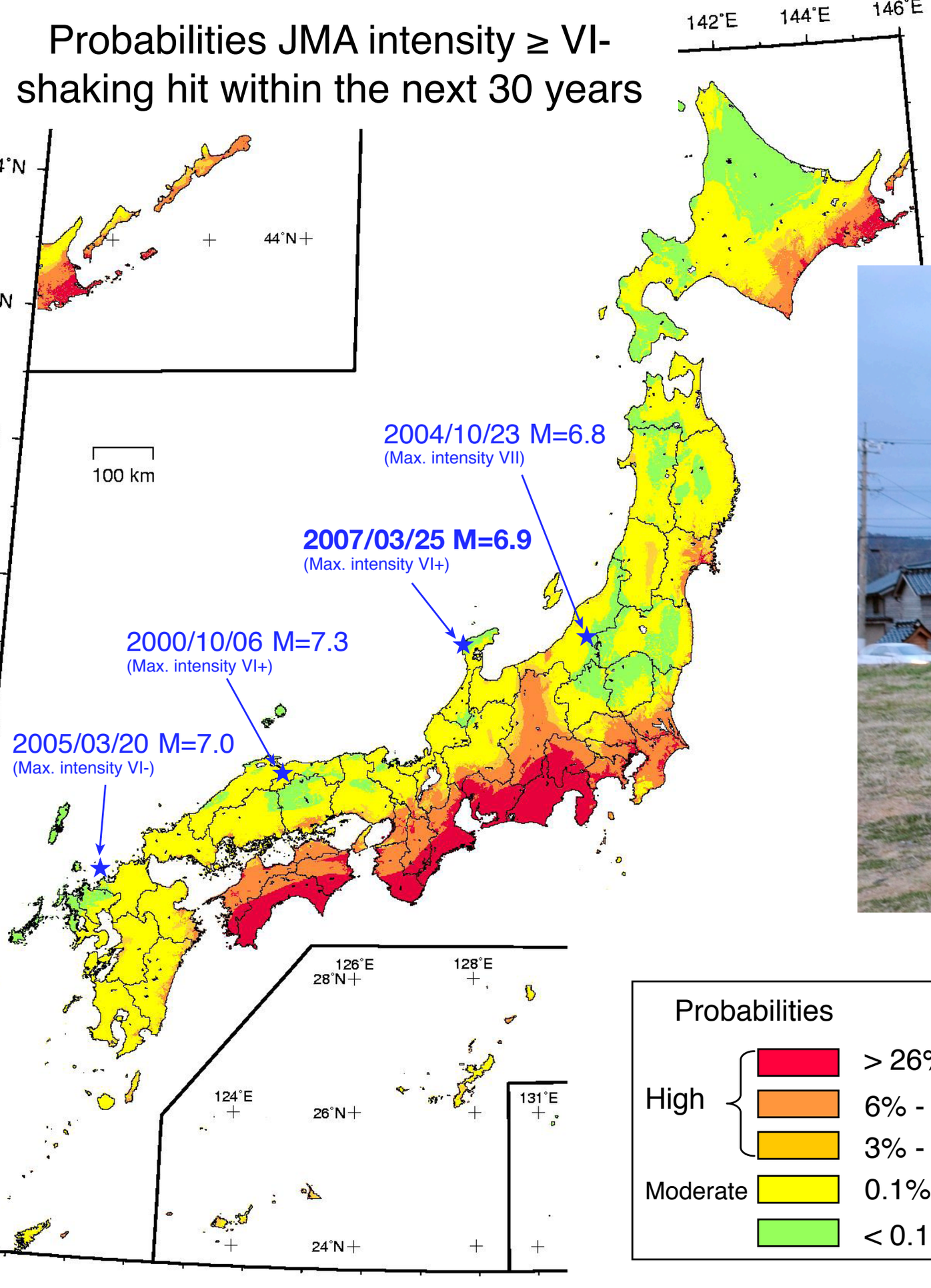


Lessons from March 25, 2007, Mj=6.9 Noto-Hanto earthquake

Probabilities JMA intensity ≥ VI- shaking hit within the next 30 years



Probabilities

High		> 26%
		6% - 26%
		3% - 6%
Moderate		0.1% - 3%
		< 0.1%

Fatalities: 1
Injured persons: 331
Houses completely destroyed: ~600
Houses partially destroyed: ~10500

Preliminary results were updated on our website immediately after the EQ

能登半島地震 | 活断層研究センター予定表

< 前のページに戻る

2007/3/26 更新

能登半島沖の地震の周辺活断層への影響

遠田晋次（地震テクトニクス研究チーム）

計算条件

【震源断層】
震央 北緯37.22°，東経136.685°
Mw = 6.7 （長さ15km，幅15km，走向58°傾斜60° レイク117°，すべり1.8m）

【受け手側断層】
走向58°傾斜60° レイク117°，深さ10km

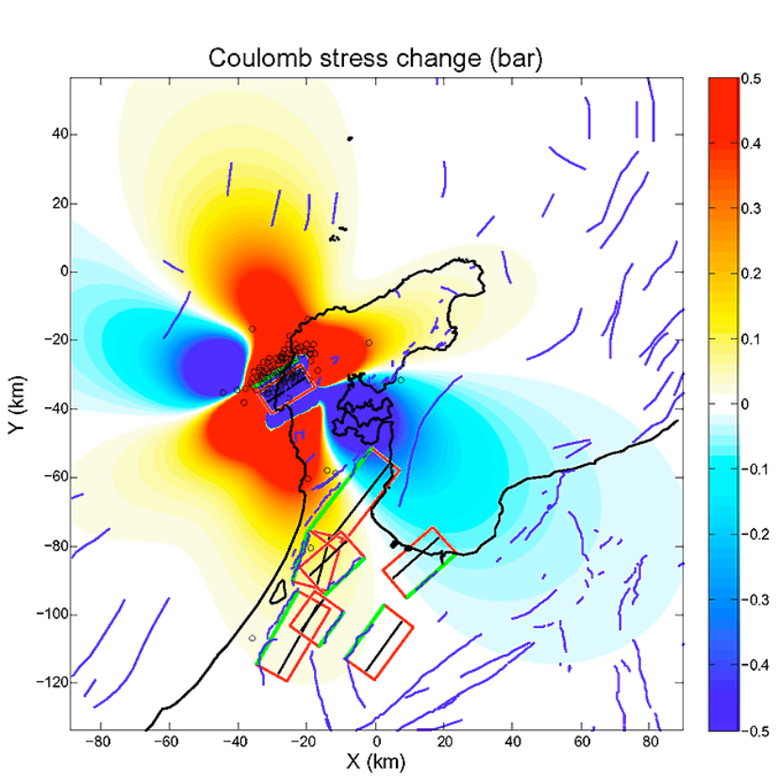
地震分布は防災科研Hi-net自動解による3月25日18:00までの余震．

【主要活断層への応力変化】

以下の活断層が，今回の震源と同様のメカニズムを持つと仮定すると，

- 邑知潟の東側の断層(石動山断層)： ごくわずかに減少
- 邑知潟の西側の断層(眉丈山断層)： ごくわずかに増加
- 森本・富樫断層 ： ほぼ変化無し
- 呉羽山断層帯 ： ごくわずかに減少
- 砺波平野断層帯 ： ほぼ変化無し
- 能登半島の確実度の低い短い活断層群 ： 半島北部顕著に増加，七尾湾周辺は顕著に減少

いずれにしても，現時点(3月25日午後6時時点)では，福岡県西方沖の警固断層のような顕著な応力変化はない．ただし，邑知潟断層帯周辺以北では，一般に微小地震活動活動に変化があるとされる0.1bar (0.01MPa) を超えている．



March 26 http://unit.aist.go.jp/actfault/katsudo/jishin/notohanto/data03.html

Coulomb 3.0.03.15 25-Mar-2007 19:44:51 Notonput5.inp
Specified faults: 58/60/117 Depth: 10.00 km Friction: 0.40

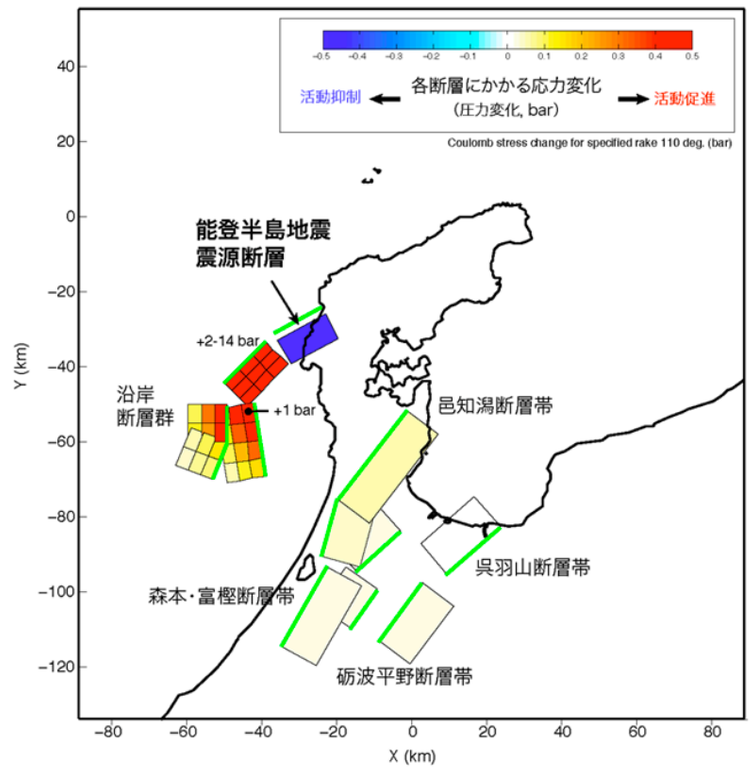
能登半島地震 | 活断層研究センター予定表

< 前のページに戻る

2007/3/27 更新

2007年3月25日能登半島地震による周辺活断層への影響評価

遠田晋次（地震テクトニクス研究チーム）

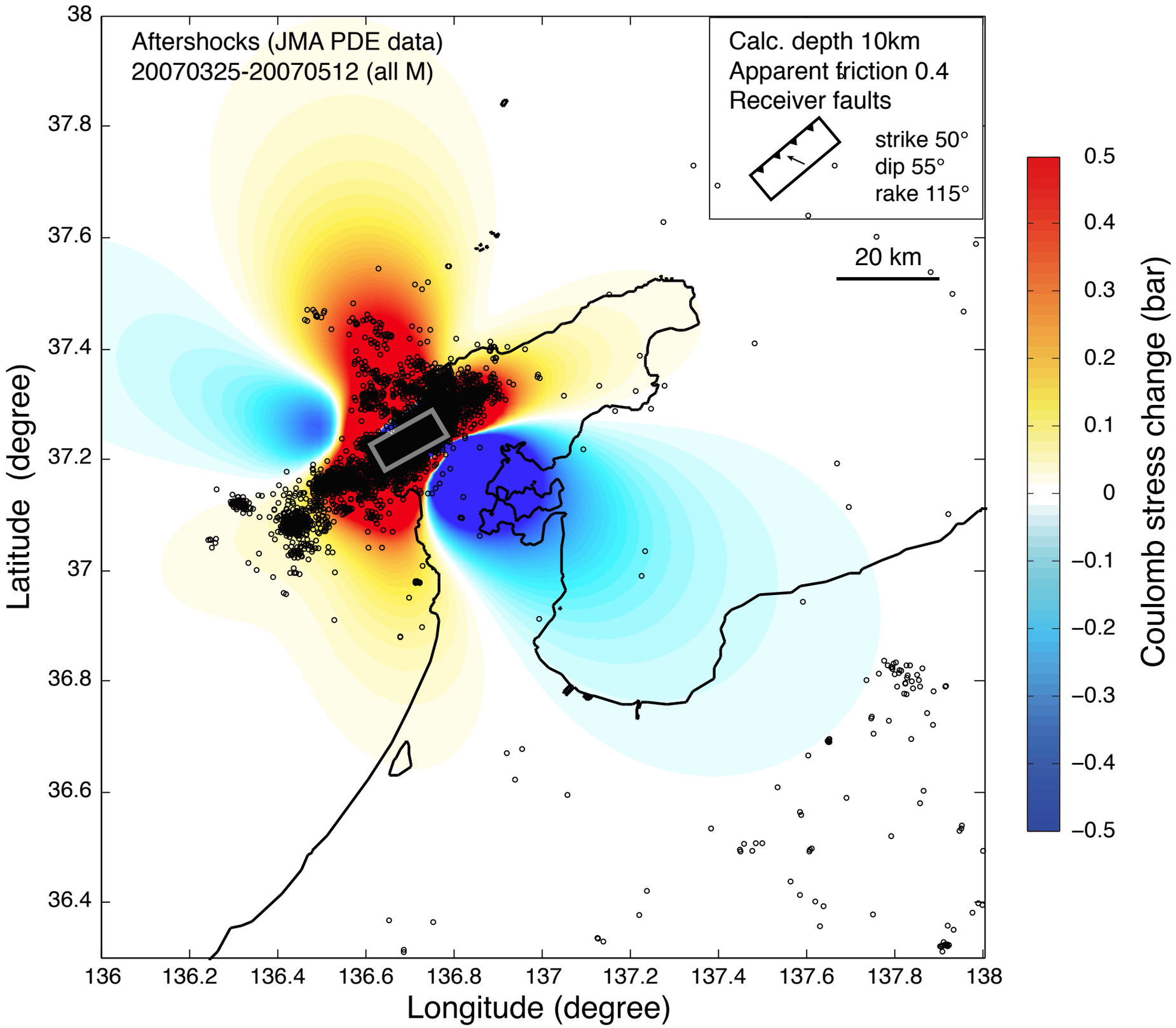


断層は地表から深さ15kmまで延びていると仮定し，その地表投影を示した．傾斜は震源断層とその西延長は60°．その他は55°とした．緑線は各断層の地表での位置を示す．沿岸断層群の位置は，能登半島西方海底地質図（産総研，印刷中）に基づく．

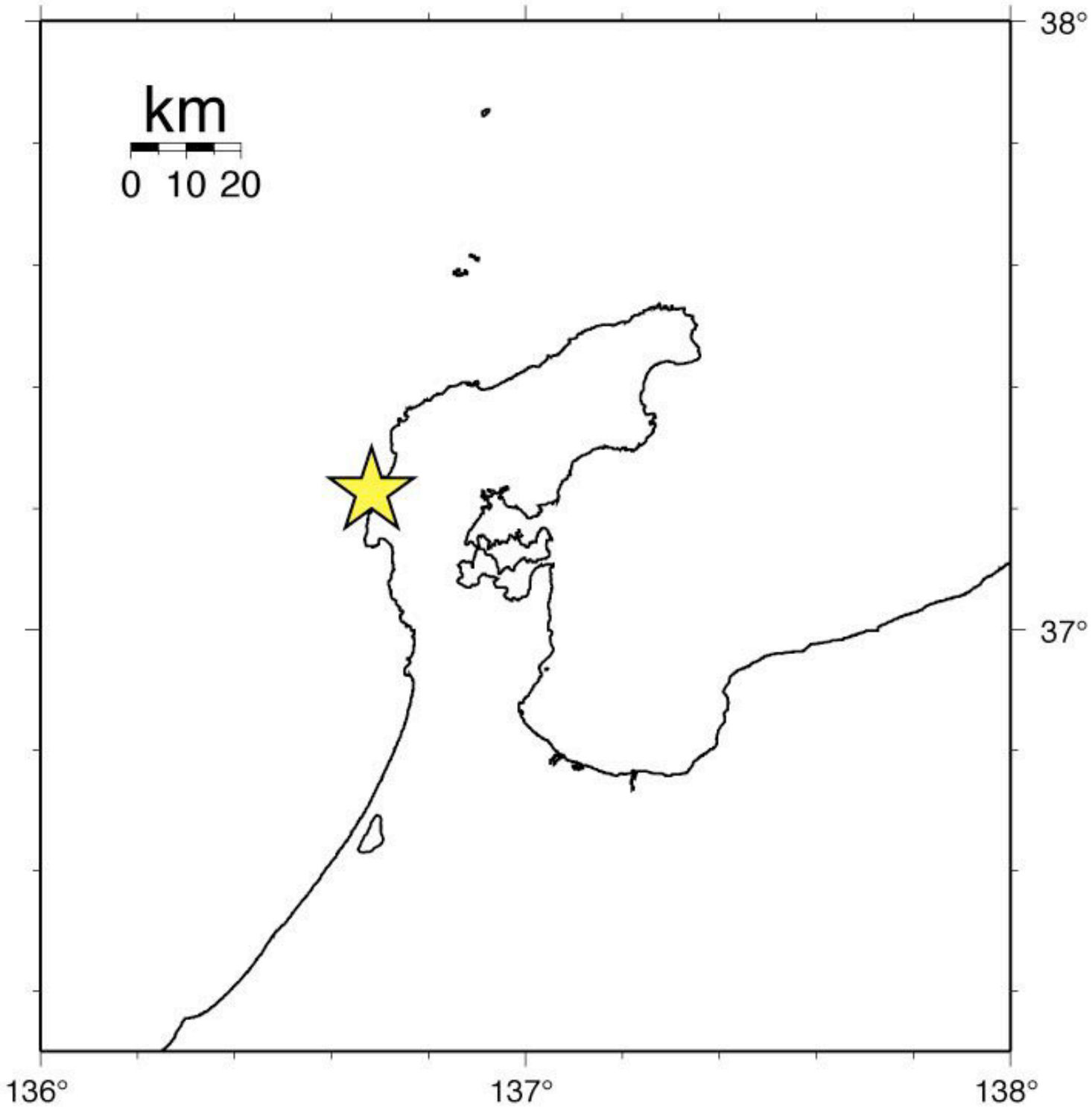
今回の地震による邑知潟断層群以南の陸上活断層への影響はごくわずかである（大気圧の1/10以下の圧力変化）．しかしながら，震源断層の西側延長部にはきわめて大きな応力変化があり，実際余震活動も活発である．また，その南に南北にのびる２条の海底活断層にも活動を促進する圧力が加わったと推定される．

March 27 http://unit.aist.go.jp/actfault/katsudo/jishin/notohanto/data04.html

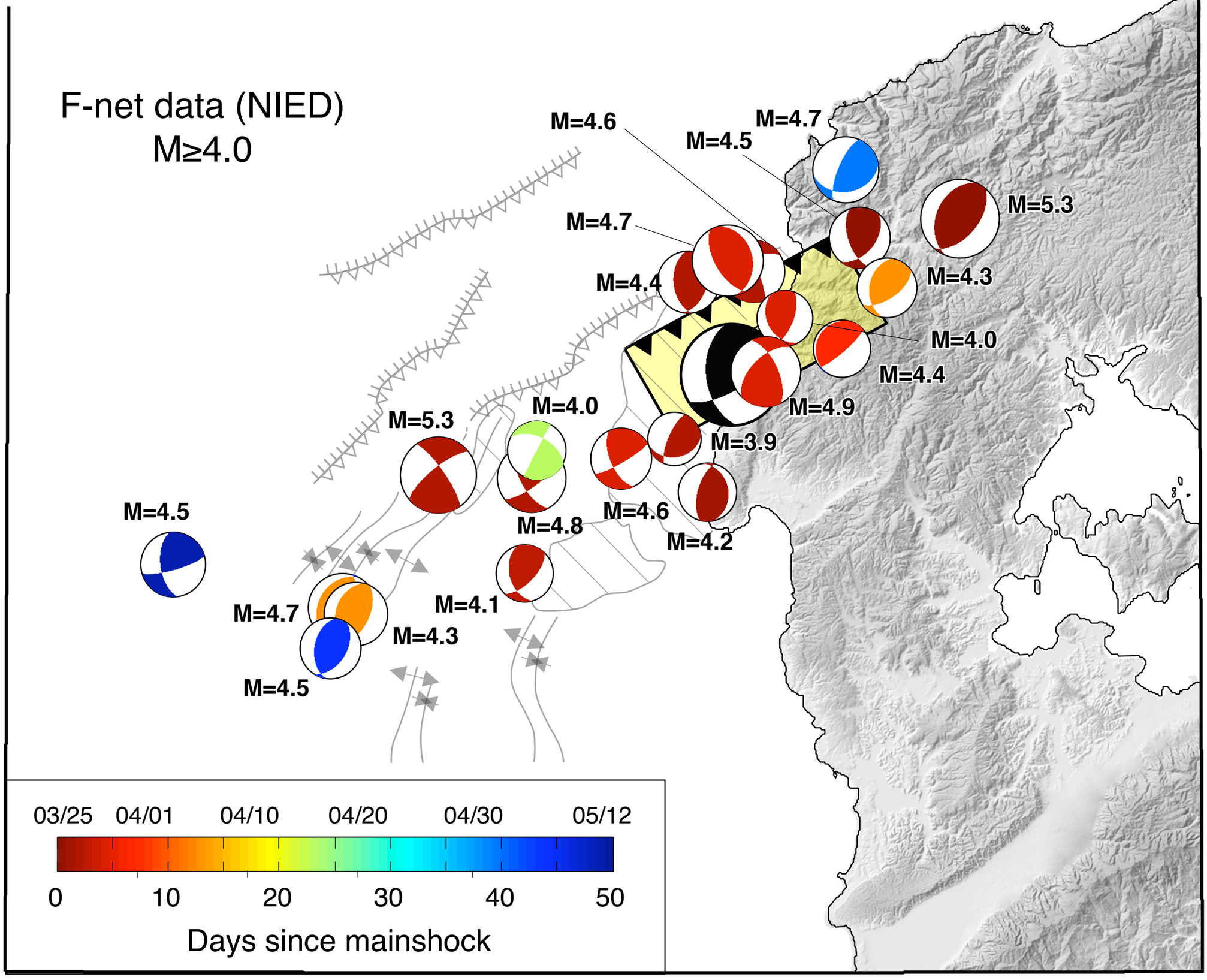
Spatial aftershock forecasting using Coulomb stress hypothesis



Aftershock zone has been expanded as a function of time

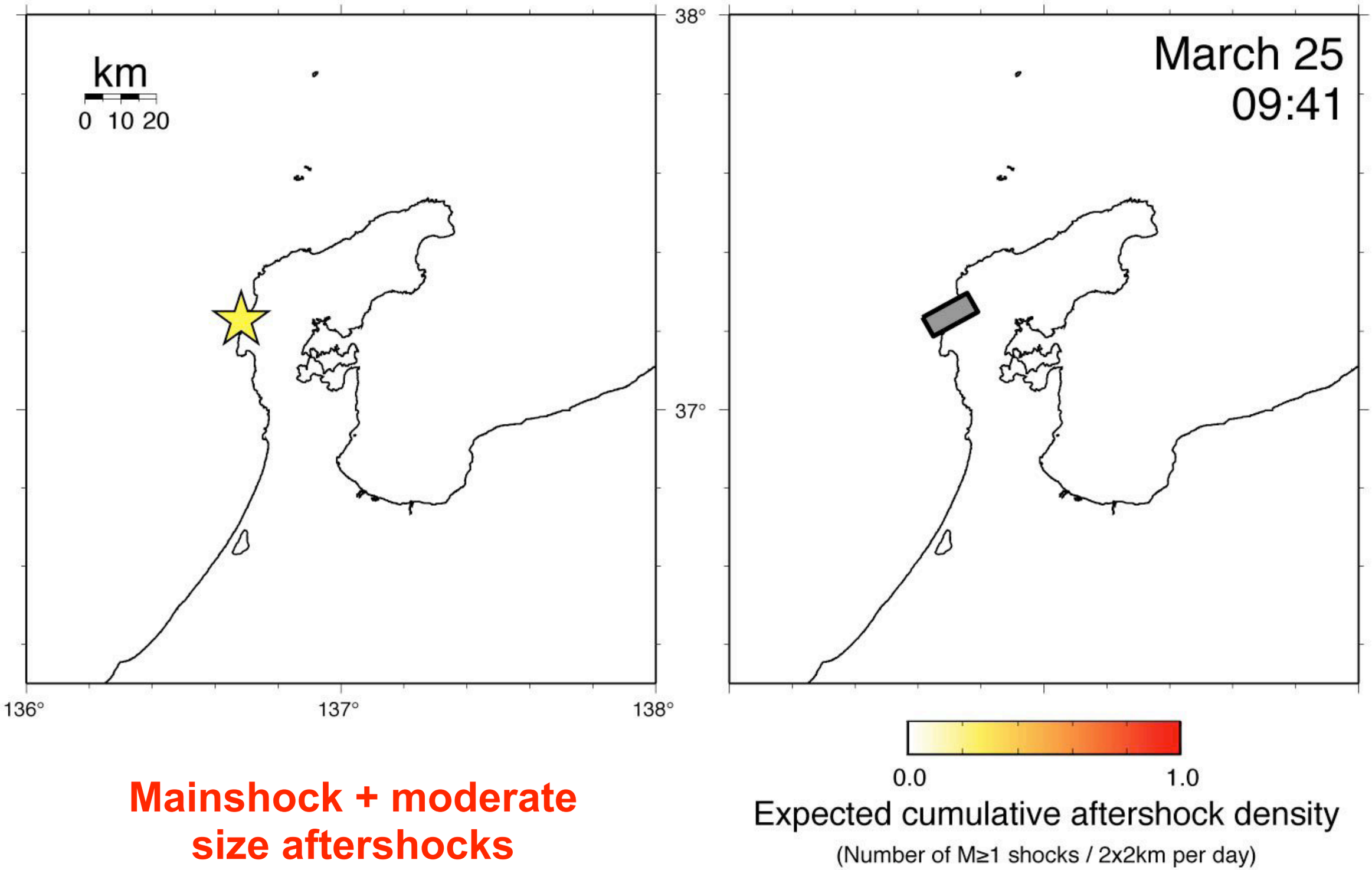


Major aftershocks may have contributed to local large aftershock generation



Spatial aftershock forecasting using Coulomb stress hypothesis

incorporating rate & state friction and background seismicity

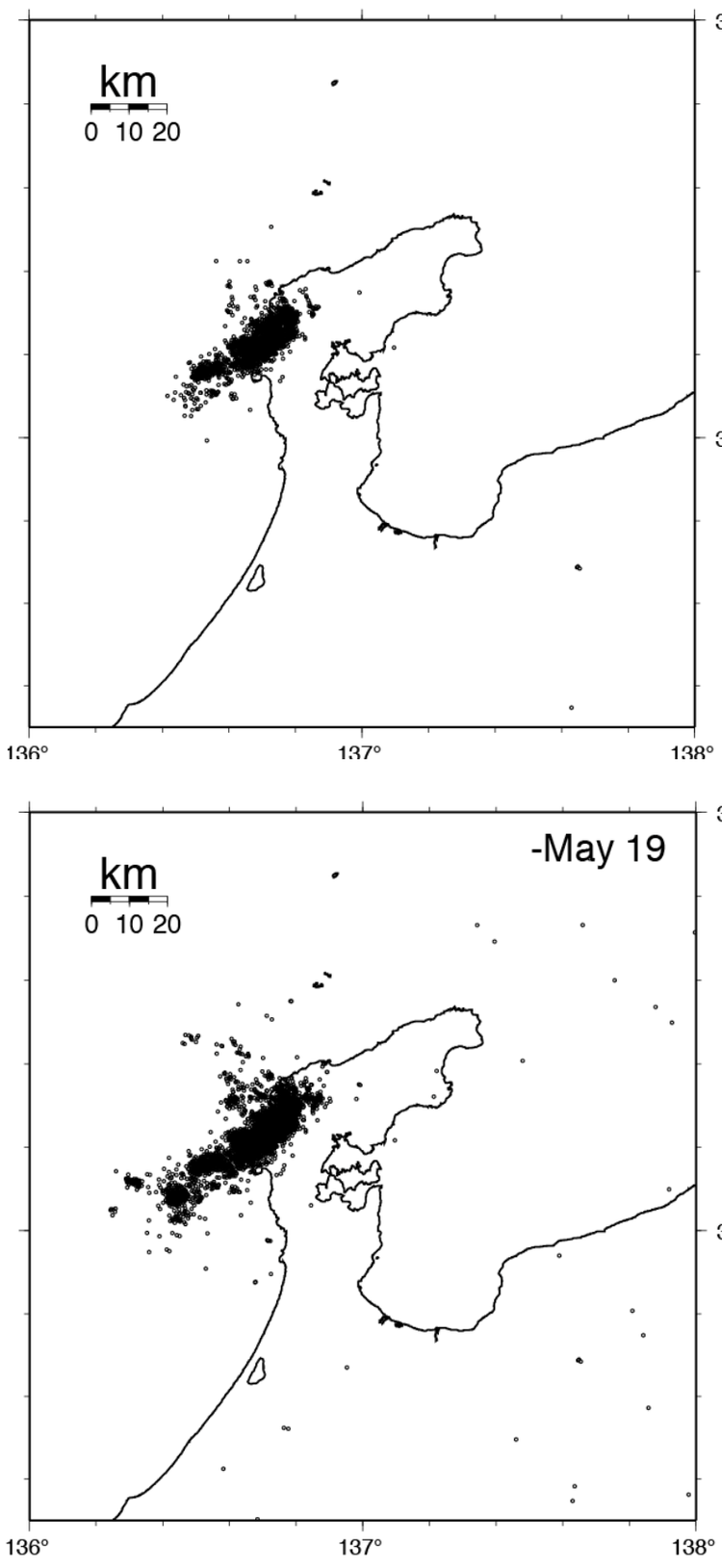


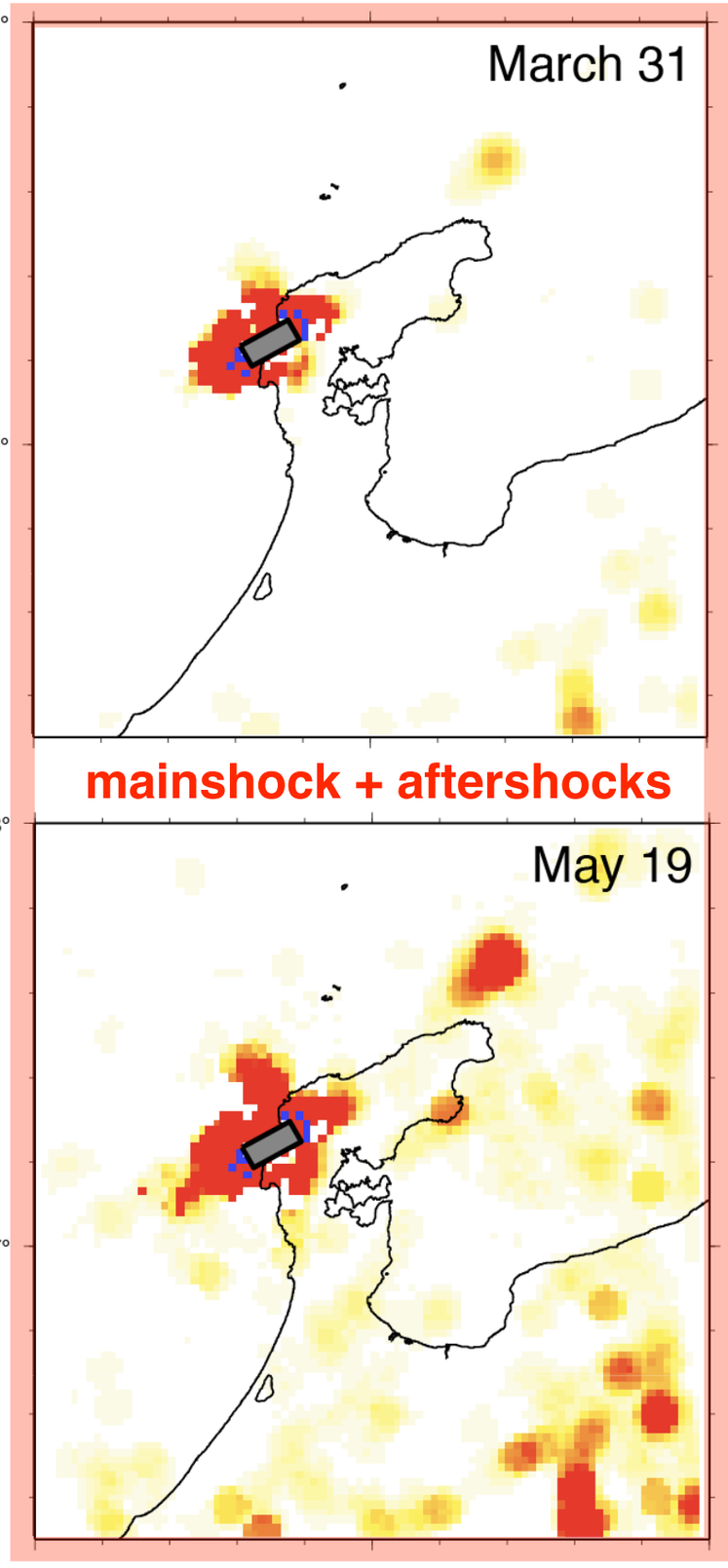
Mainshock + moderate size aftershocks

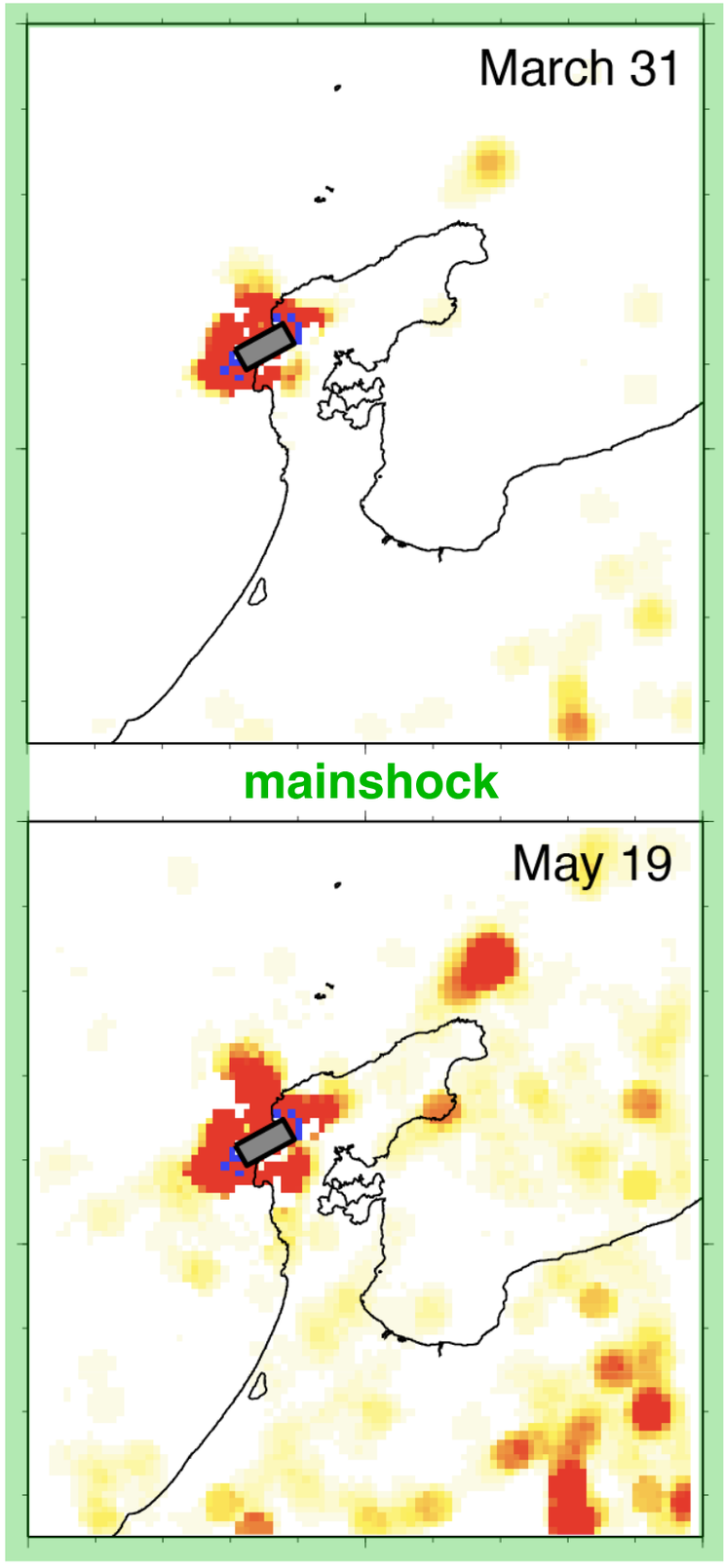
Mainshock + moderate aftershocks vs mainshock only

6 days after

25 days after







Rapid expansion of aftershock zone may suggest A*sigma is really small

March 30, 2007 (5 days after mainshock)

km
0 10 20

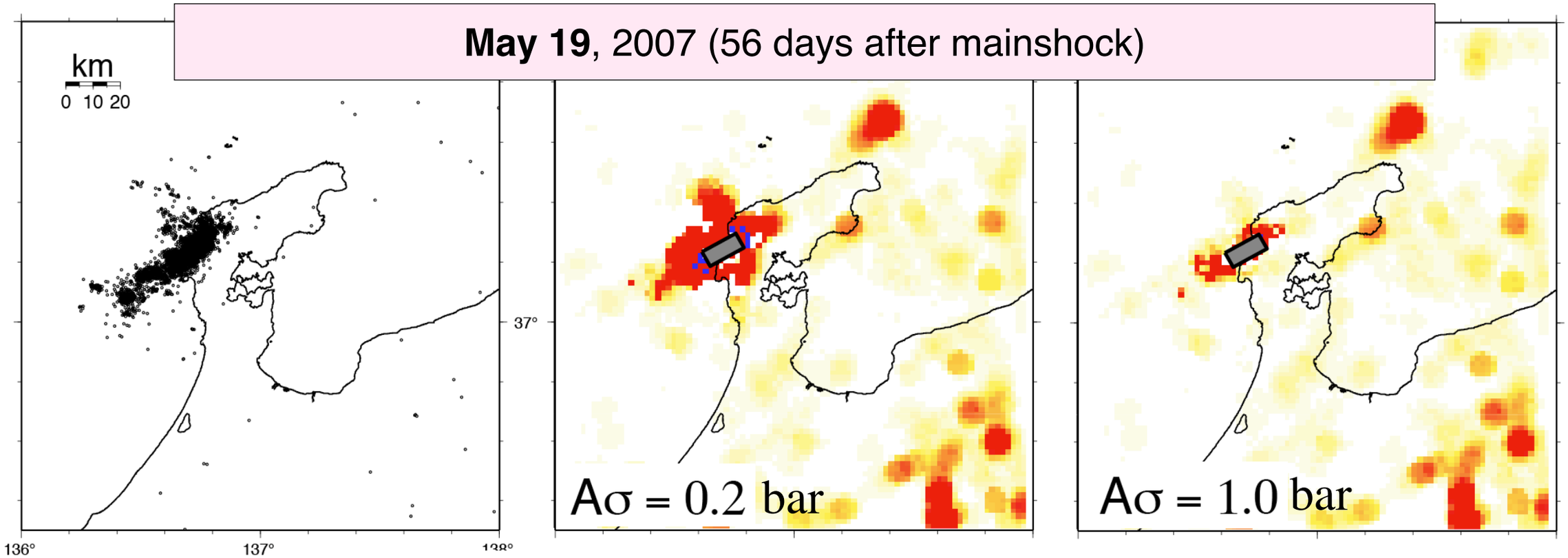
Aσ = 0.2 bar

Aσ = 1.0 bar

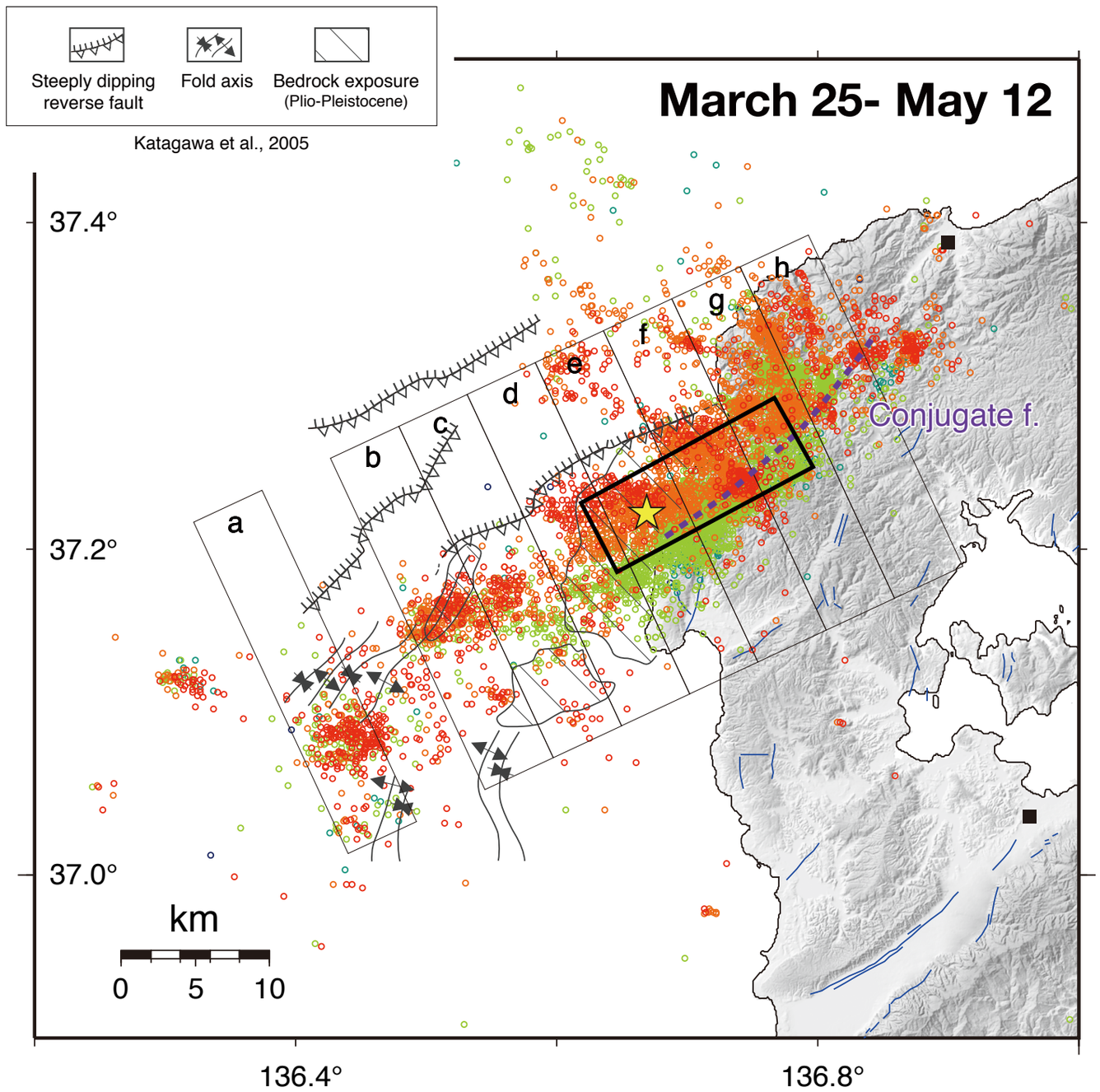
136° 137° 138°

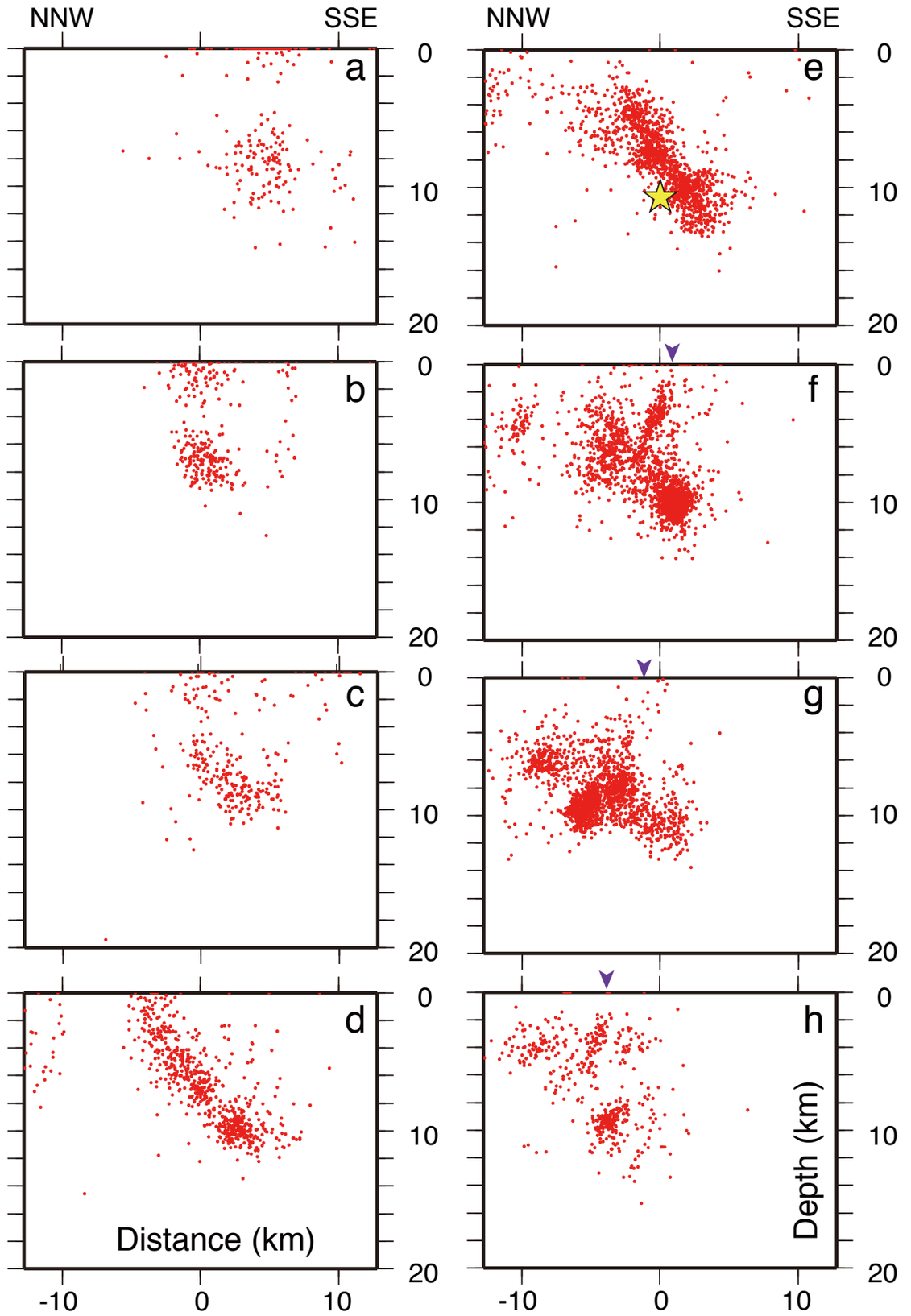
37°

May 19, 2007 (56 days after mainshock)



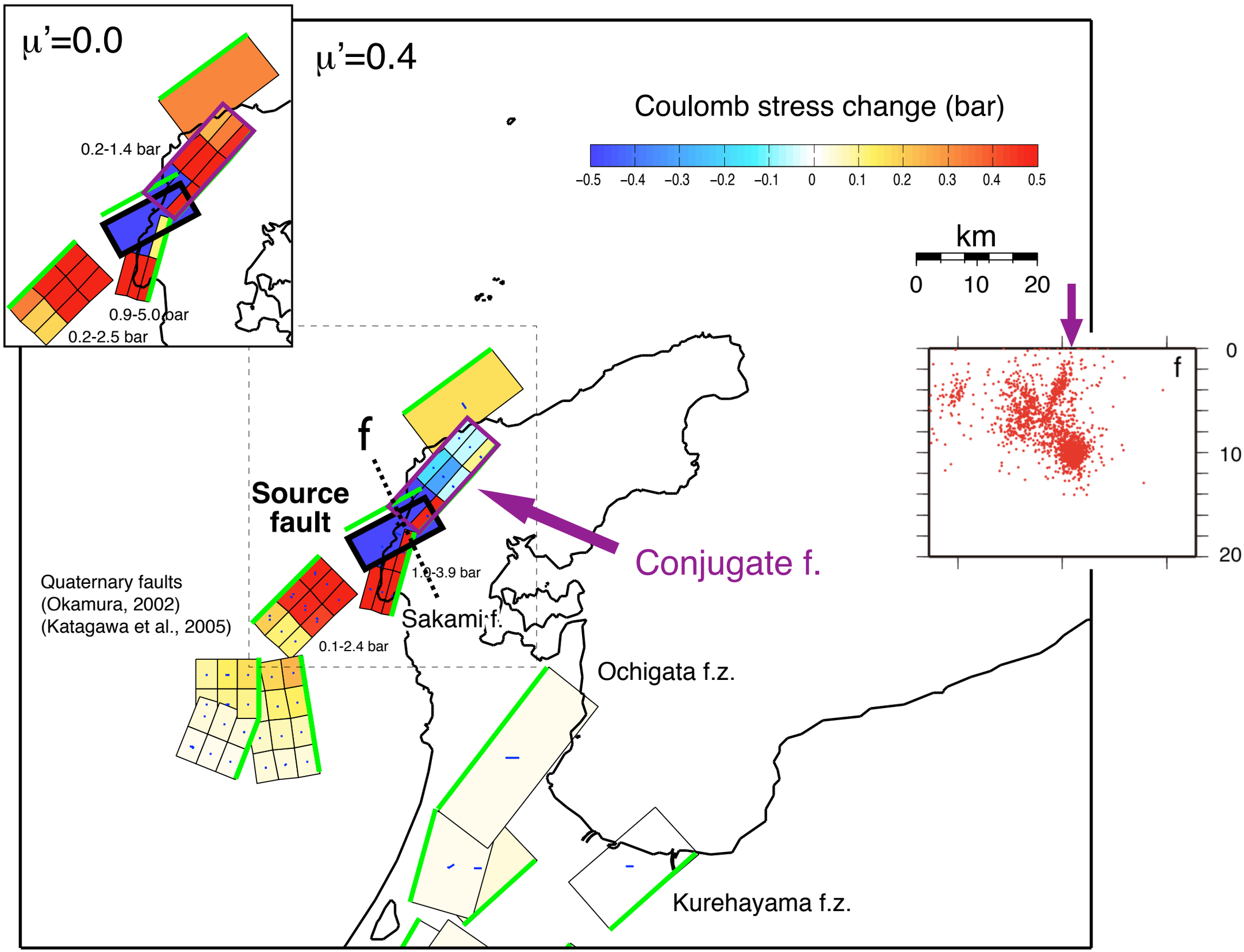
Source fault dip over 45° suggests low apparent friction



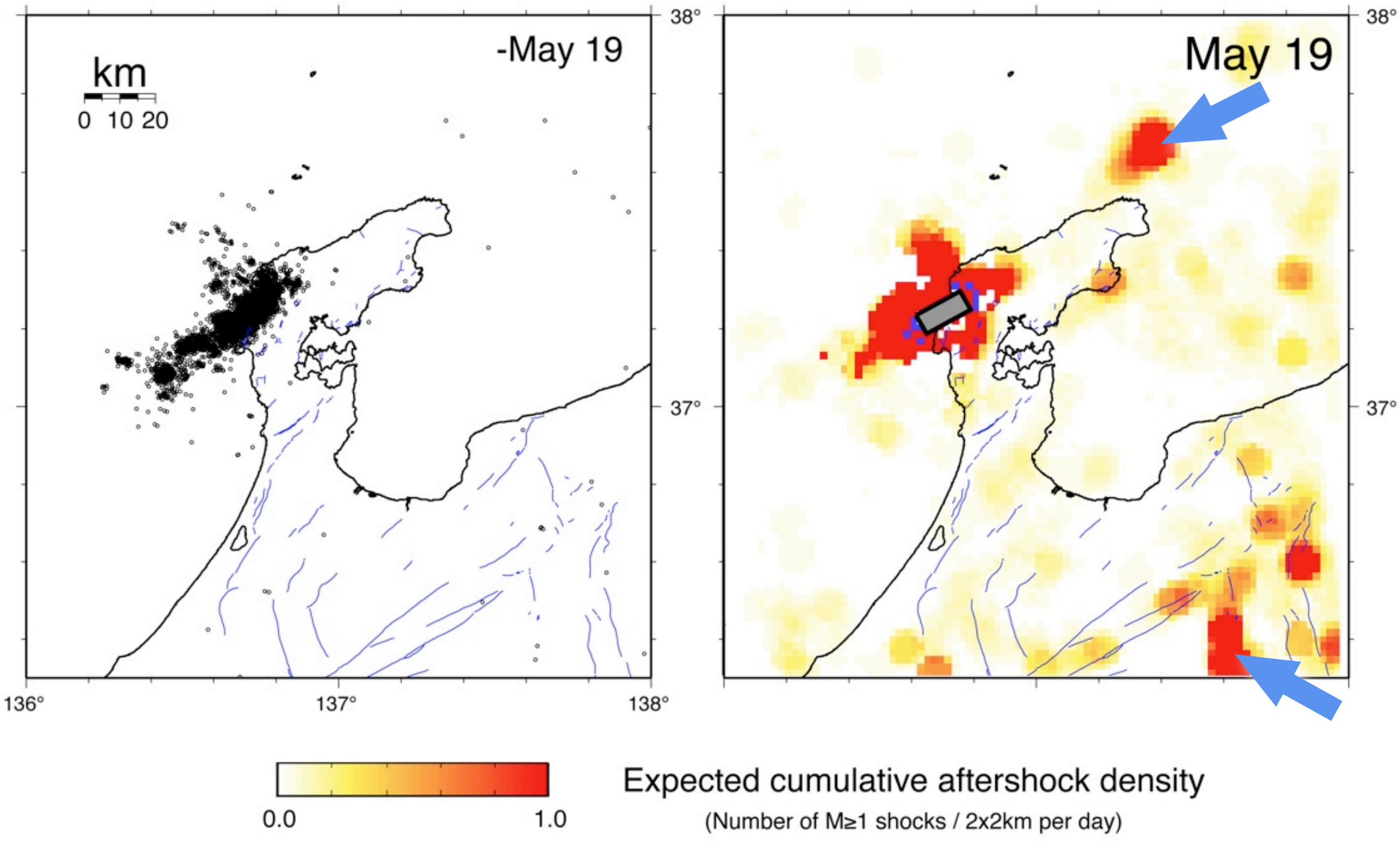


Aftershocks are abundant along inactive geologic faults nearby

Activate a conjugate fault also suggests low apparent friction

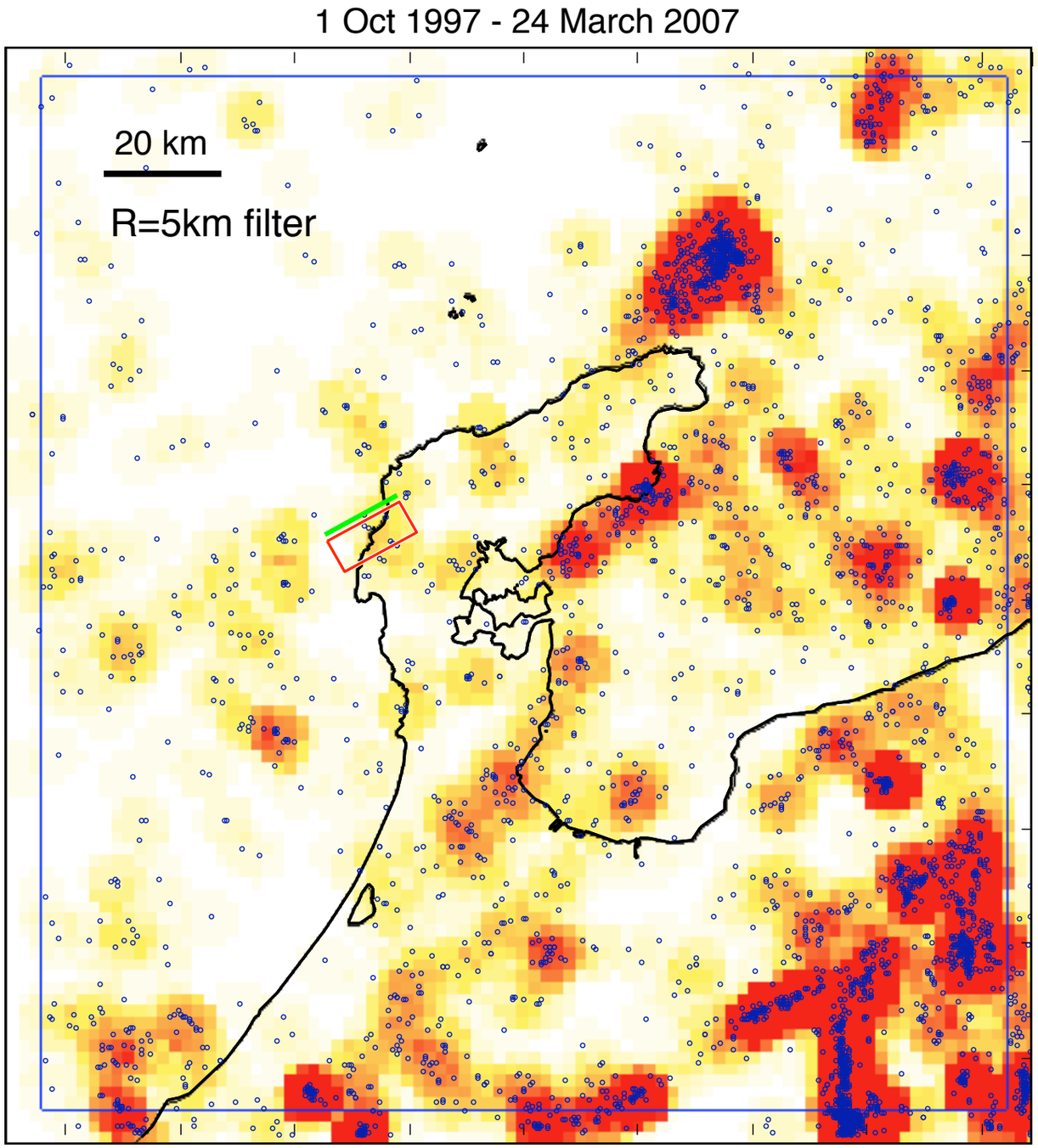


Wrong estimate of reference seismicity rate leads mis-forecast

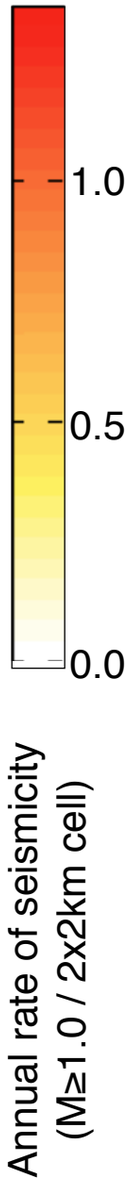


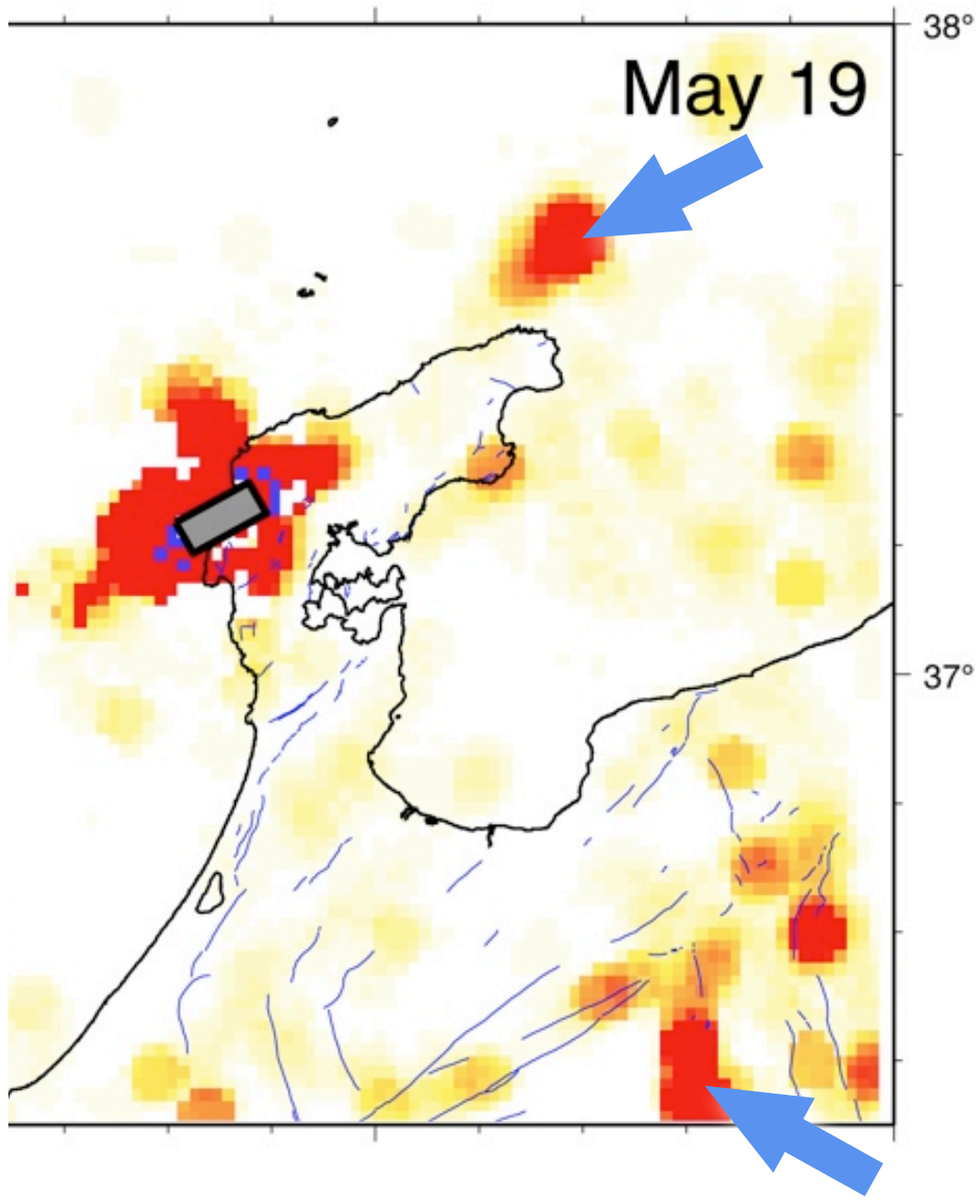
Why wrong prediction?

Wrong estimate of reference seismicity rate may lead mis-forecast



Reference seismicity rate

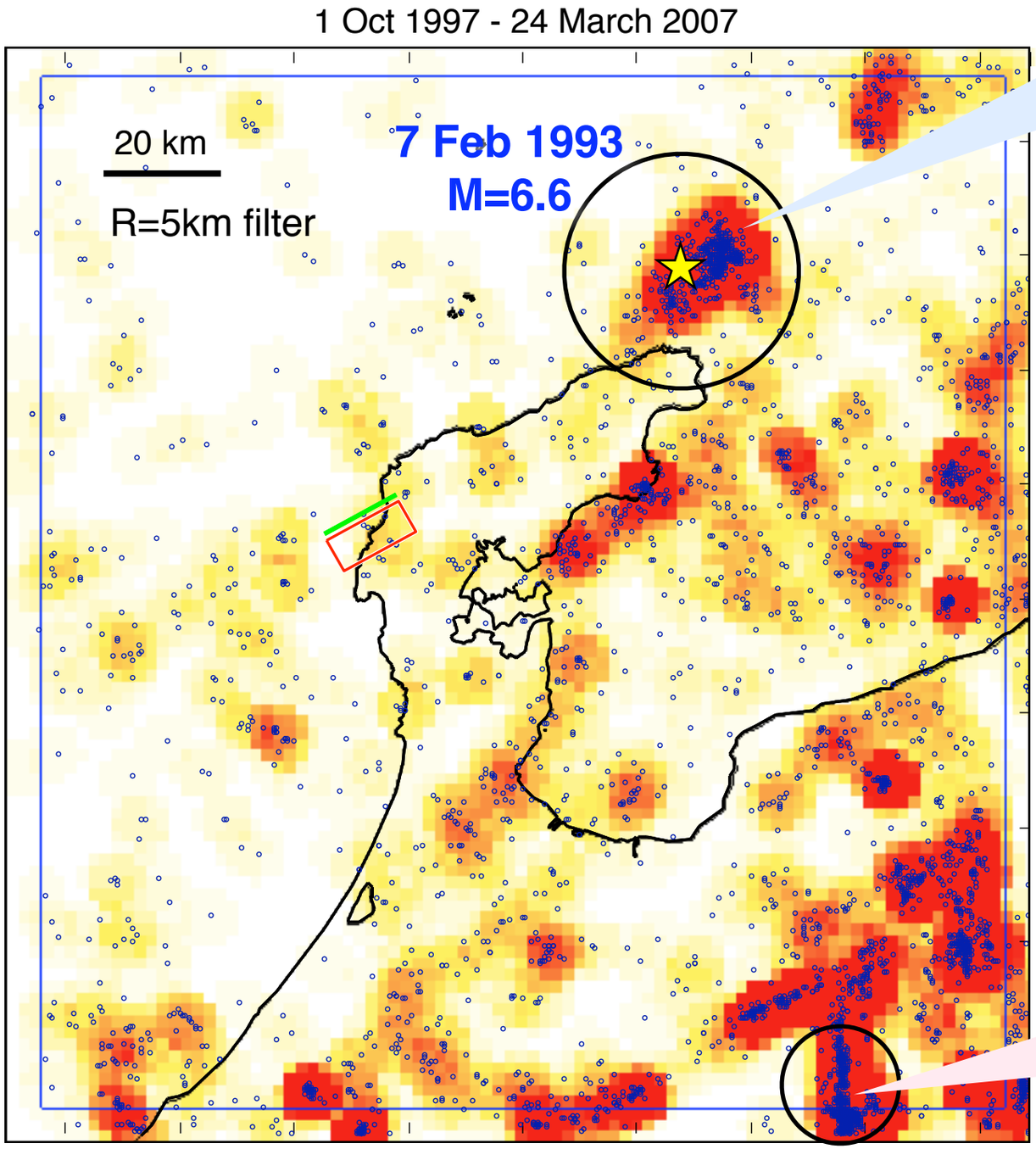


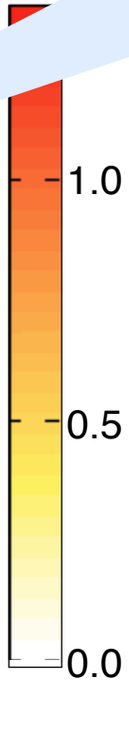


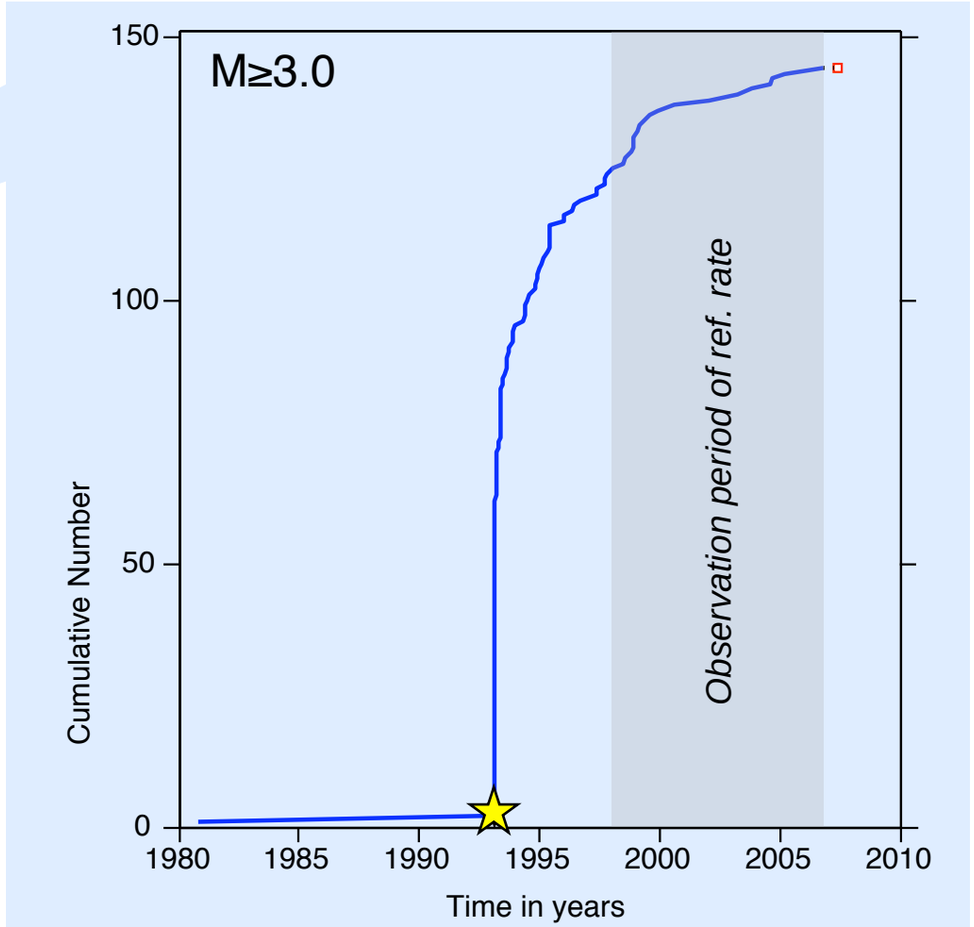
nulative aftershock density

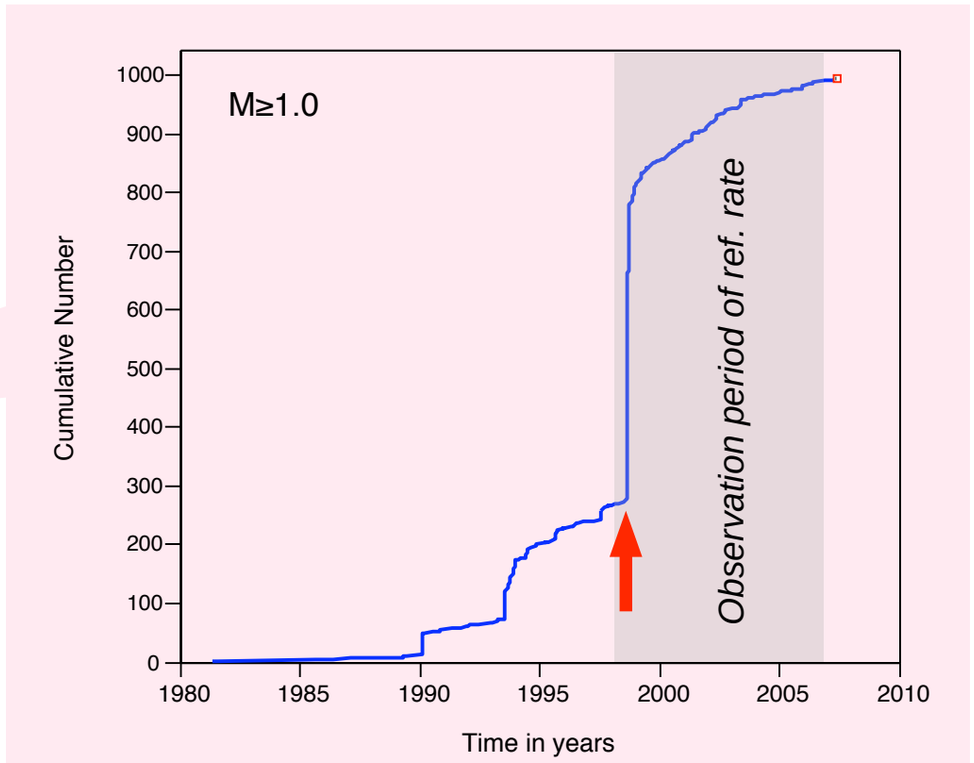
f M≥1 shocks / 2x2km per day)

Overestimated background seismicity due to recent events









$$R_n = \frac{r}{\gamma_n \dot{\tau}_r}$$

Conclusion & implications

- As well as statistical models, Coulomb hypothesis with r/s friction also suggests that any size of earthquake increases chance of subsequent shocks nearby.

- So moderate to large aftershocks are not only the consequence of mainshock stress change but also contributing to the subsequent aftershocks even large earthquake triggering.

- Near real time forecasting incorporating such larger aftershocks would perform better than mainshock only.

- To optimize the rate/state parameters, we need frequent feedbacks from real-time data during the forecasting process. A*sigma and precise reference rate of seismicity would be critical issues to better forecast aftershock hazard.